Nankai University

Research Seminar

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Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Micro Manipulation for Precision Manufacturing and Biomedical Applications

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New Zealand is located in the South Pacific between the Pacific Ocean and the Tasman Sea, between latitude 35 and 45 degrees south.

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Liveable Place

- In 1996, Christchurch was acknowledged as the outstanding garden city from 620 international entries.
- In 1997, Christchurch was judged Overall Winner of Major Cities in the Nations in Bloom International Competition to become 'Garden City of the World'!

"I think every person….. dreams of finding some enchanted place of beautiful mountains and breathtaking coastlines, clear lakes and amazing wildlife. Most people give up on it because they never get to New Zealand"

Mr. Bill Clinton – Former US President
Gala Dinner, Christchurch, NZ 2000


Dr XiaoQi Chen's Office
Dept of Mech Eng
University of Canterbury

Agenda

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- Overview of Mechatronics@UC
- Precision Assembly For Optical MEMS Switch Packaging
- Microrobotic Cell Injection
- Force Pattern Characterization of C. elegans
- Conclusions

Who are involved

- Supervising Team:
  - Assoc Prof XiaoQi Chen (Director for Mechatronics) - robotics, mechatronic systems
  - Prof J Geoff Chase - dynamics and control, bioengineering, structural
  - Dr Wenhui Wang - robotics, bio-mechatronics
  - Dr Stefanie Gutschmidt - dynamics and vibration
  - Dept of Electrical Engineering, Computer Science, MacDiarmid, HITLab, Bioengineering Centre
- Technical Support
  - Mechatronics and electronics technicians: Rodney Elliot, Julian Murphy, Julian Philips,
  - Mechanical workshop
- Postgraduates
  - James Pinchin, PhD - Low-cost GPS based attitude solution using multiple software based receivers.
  - Patrick Wolm, MEng – Dynamic stability control of front wheel drive wheelchairs.
  - Scott Green, PhD - Human Robot Collaboration Utilising Augmented Reality
  - Ali Ghanbari, PhD – MEMS actuation and precision micromanipulation.
  - Mostafa Nayyerloo, PhD, – Structural health monitoring
  - Chris Hardie, MEng – biologically inspired robots
  - Matthew Keir, PhD – Head motion tracking, graduated in 2008
- Visiting Researchers / Fellows
  - Prof Richard King, Oregon Institute of Technology, Jun 2006 – Mar 2007
  - Prof Clarence de Silva, University of British Colombia, 1-31 August 2008
  - Australian DEST Endeavour Fellowship, Mr Ben Horan, Aug – Dec 2008. Haptics technology
- Interns
  - Julien Dufeu, Institut Francais de Mecanique Avancee (IFMA), 2007. Modelling of wall climbing device
  - Matthias Wagner, the University of Munich, 2007. Design of wall climbing robot.
  - Nikolas Schaal, The University of Stuttgart, 2007. Design of underwater vehicle.
  - Richard Engelaar, Eindhoven University of Technology, 2008. underwater vehicle.
  - Johan Vervoort, Eindhoven University of Technology, 2008. underwater vehicle.
  - Harald Zophoniasson, ENISE, France, 2008. High-precision motorised stage
- Industrial Collaborators
  - Geospatial Research Centre, Dynamic Controls Limited, Industrial Research Limited (IRL), Commtest, etc.

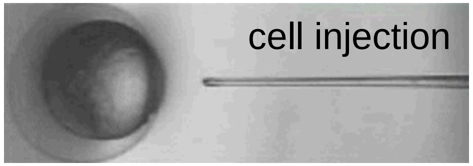
Mechatronics@UC

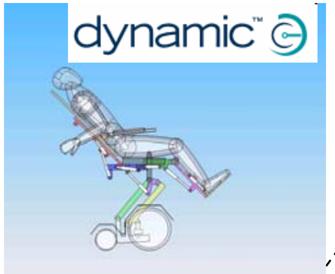
Bio-mechatronics

- Assistive devices for rehabilitation
- Bio-micromanipulation – cell injection

Burwood Academy *of* Independent Living

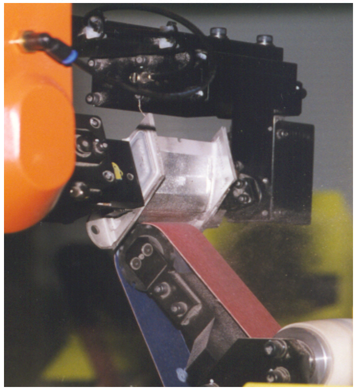
INDUSTRIAL RESEARCH LIMITED

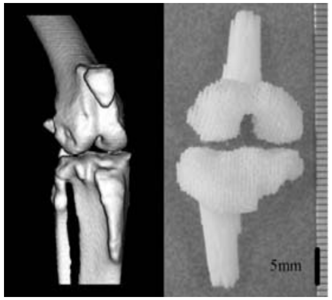




Instrumentation and Automation

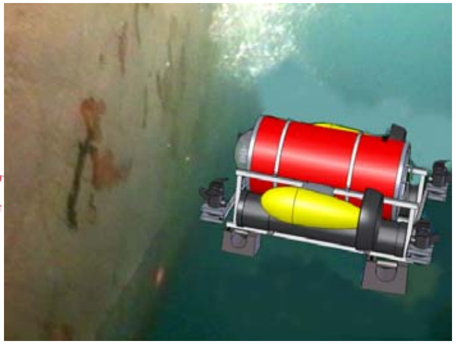
- Manufacturing
- Structural control
- Energy harvesting
- Bio-scaffolding





NIWA
Taihoro Nukurangi

HITLabNZ



Geospatial
Research Centre

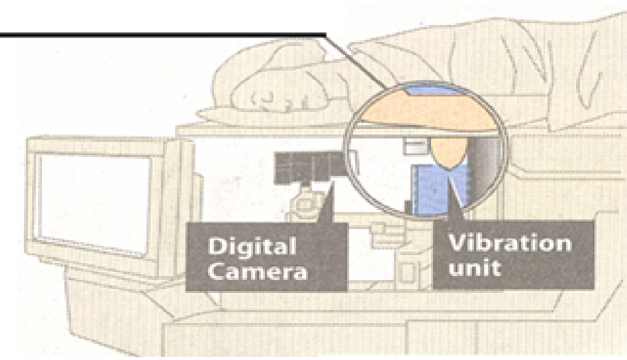
Mobile Robotics

- Unmanned aerial vehicle, micro air vehicle
- Underwater vehicle for bio-security inspection
- Wall-climb robot for tank welding

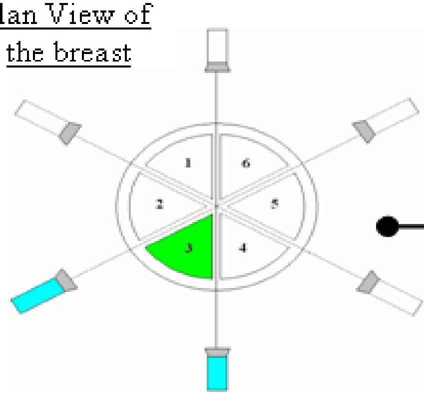
Digital Image-Based Elasto-Tomography

The DIET system is broken down into 4 fundamental steps: (1) Actuation → (2) Image Capture → (3) Motion Tracking and measurement → (4) Tissue stiffness reconstruction

1. A woman's breast is vibrated by an actuator and imaged with high-resolution digital cameras.

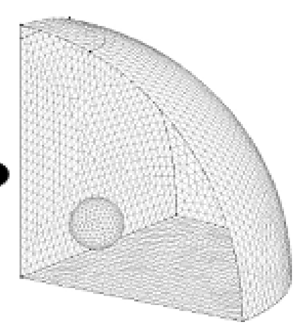


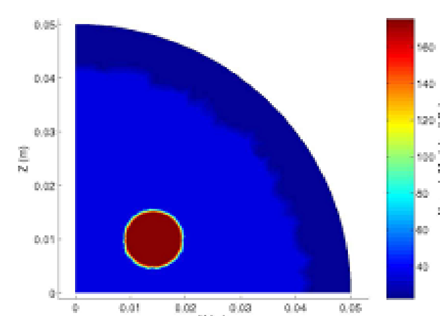
Plan View of the breast



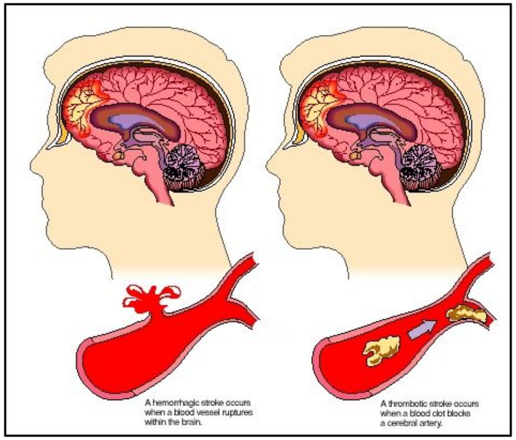
2. Spatially calibrated digital cameras combined with a motion sensor measures the surface motion of the breast.

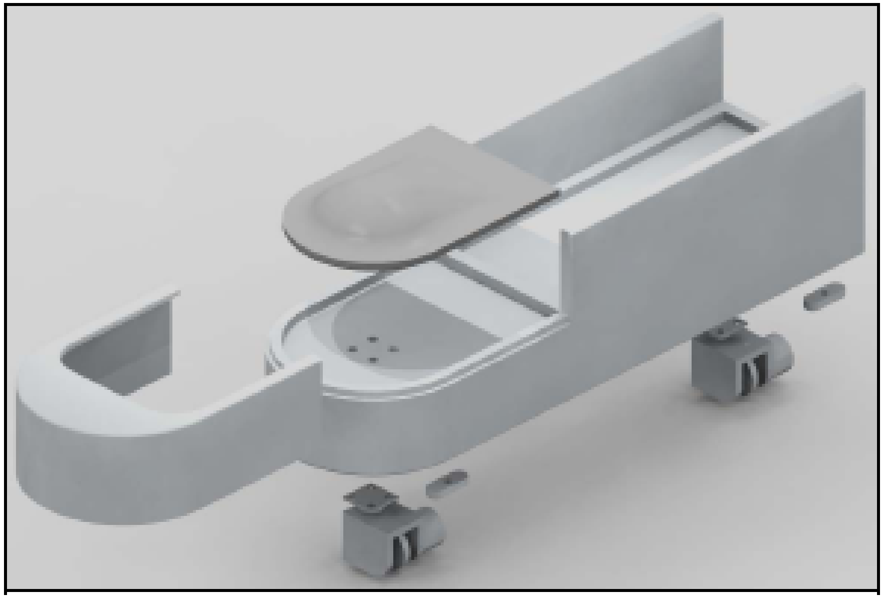
3. Finite Element method converts the measured breast surface motion into a 3-D stiffness distribution, where regions of high stiffness suggest cancer.





Variable Resistance Rehabilitation Device





Provisional Patent (2008)

UC Wall-Climbing Robot - Performace

The robot is able to transverse the gaps on the wall

High manoeuvrability in every direction, and on different surfaces.

Total weight: 234g
Max attraction force (at 5 bar): 12N

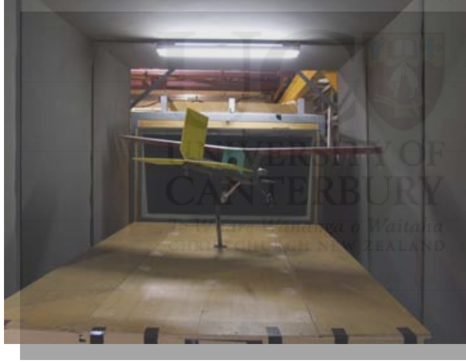
Additional weight that can be lifted (on a wall as on a ceiling): 500g

Video: Climbing different surfaces and ceiling

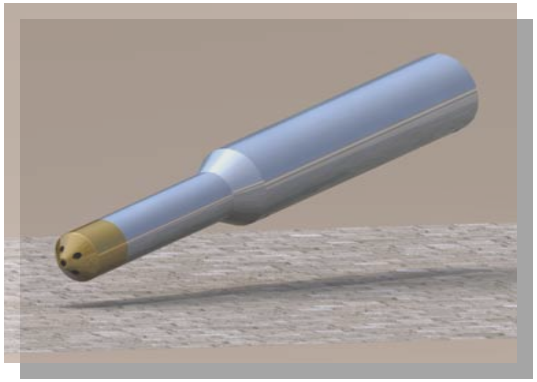
Provisional Patent (2008)

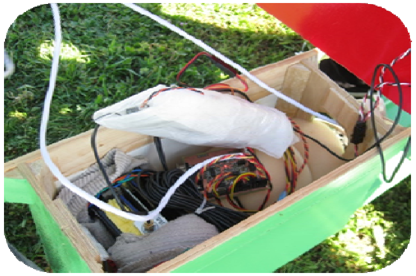
M. Wagner, X.Q. Chen, W.H. Wang, and J.G. Chase (2008), “A novel wall climbing device based on Bernoulli effect”, Proc 2008 IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA08), ISBN: 978-1-4244-2368-2, Beijing, China, October 12-15, pp. 210-215. (Best Student Paper Award).

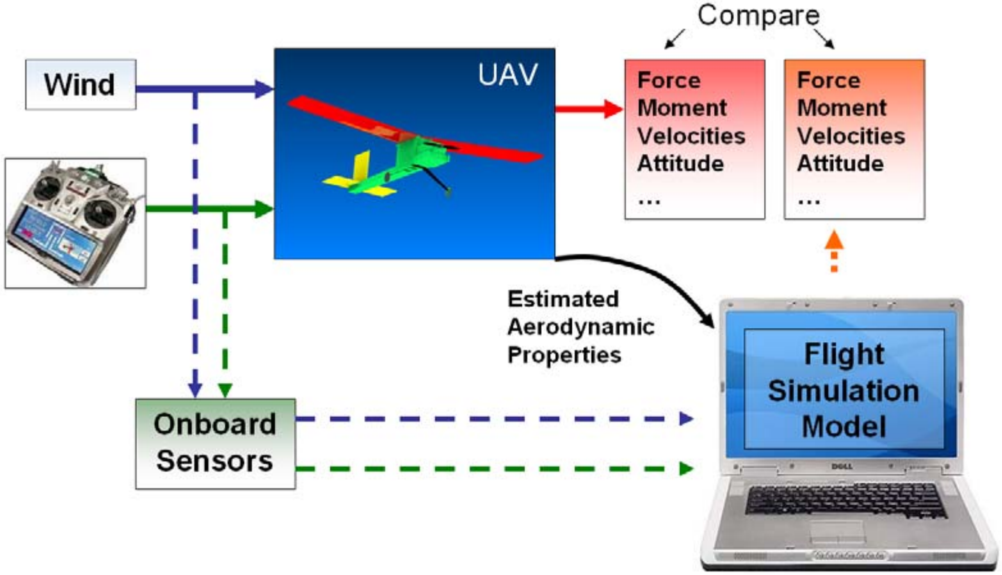
FDM Validation with On-Board Instruments



- Equipment used
  - 2.4 meter wing-span gas powered RC plane
  - GPS base station
  - Inertia navigation system
  - Servo pulse acquisition device
  - Wind speed sensor
  - Data logger
  - Wind tunnel







Video: UAV Test

D. R. Wong, Q. Ou, M. Sinclair, Y. J. Li, X. Q. Chen, A. Marburg (2008). **"Unmanned Aerial Vehicle Flight Model Validation Using On-Board Sensing and Instrumentation", 15**th Intl Conf on Mechatronics and Machine Vision in Practice (M2VIP), Auckland, New Zealand, Dec 2-4, CD-ROM.

Canterbury UUV - Biosecurity

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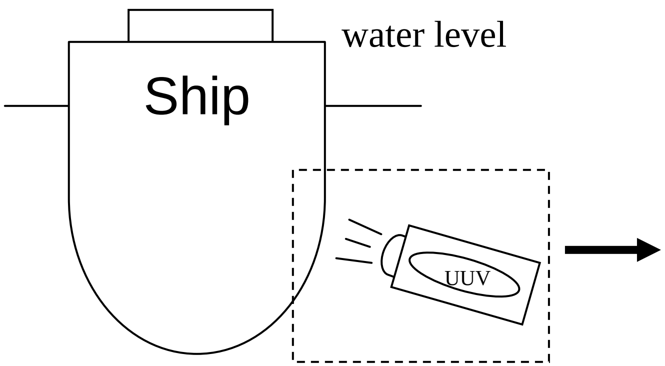
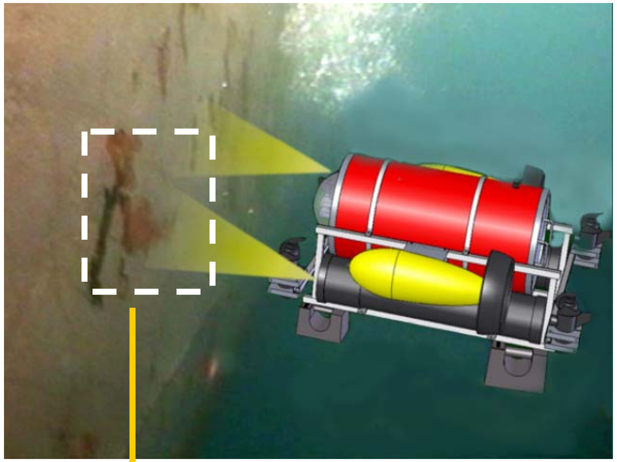
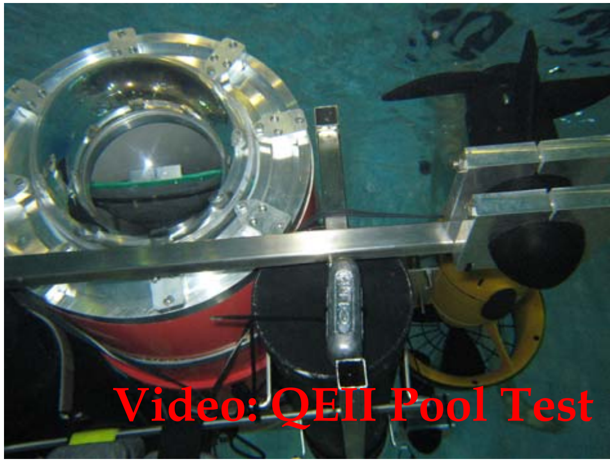
For shallow waters, up to 20m depth





sea chest



Back

W.H. Wang, R.C. Engelaar, X.Q. Chen & J.G. Chase, "The State-of-Art of Underwater Vehicles – Theories and Applications" *Mobile Robots - State of the Art in Land, Sea, Air, and Collaborative Missions*, Editors: X.Q. Chen, Y.Q. Chen, and J.G Chasse, ISBN 978-3-902613-39-4, I-Tech Education and Publishing, Vienna, Austria. (In press).

Flexure-Based Precision Assembly of Optical MEMS Switch Packaging

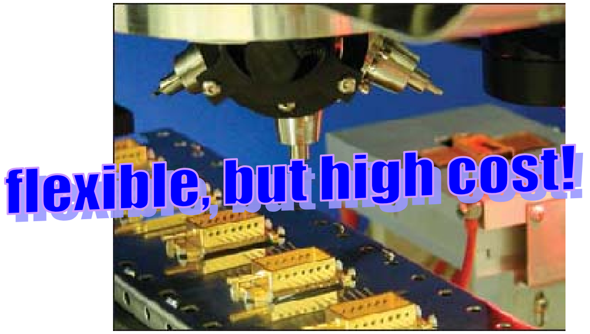
Background

➢ **State of the art: automated micro-assembly**

- **Active micro-assembly (sensor-based)**
  - **Servoing with force sensors**

    (ESEC, Switzerland; Klocke Nanotecknik, Germany)
  - **Servoing with vision image**

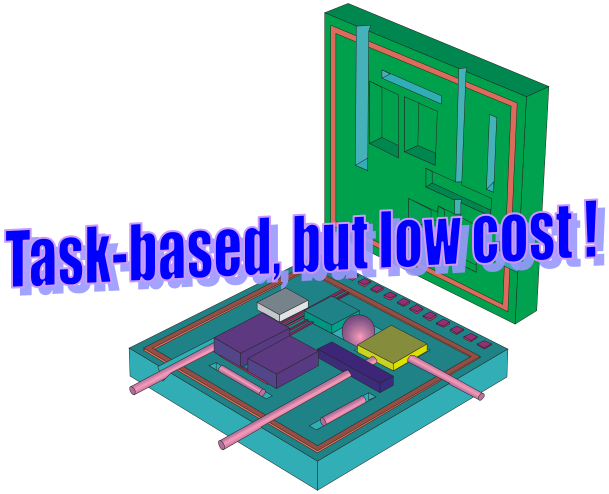
    (Universal, USA; Sandia, USA)



- **Passive micro-assembly (task-based)**
  - **Positioning fibers by V-grooves**

    (Suss MicroTec, USA, Lucent, USA)
  - **Positioning micro chips by silicon optical benches**

    (Sysmelec, Switzerland; AXSUN, USA)



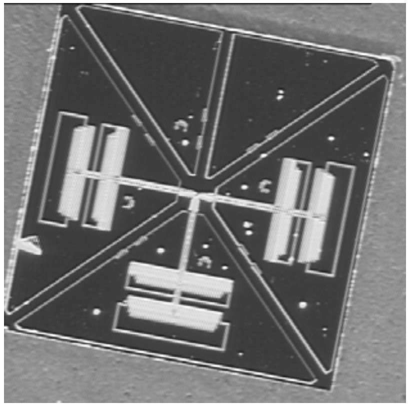
Background

➢ Objective of Research

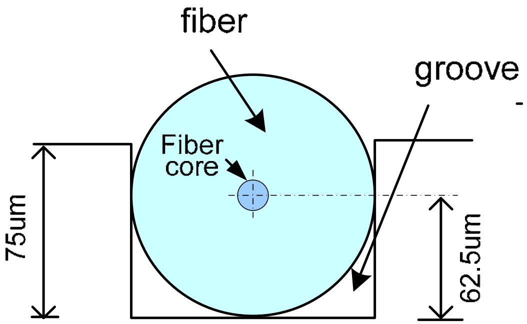
To develop a low-cost, robust and efficient method for those micro assembly tasks needing insertion operation.

- **Test-bed:**

Assembly of optical MEME switches



An optical switch with one input channel and four output channels, developed by SIMTech



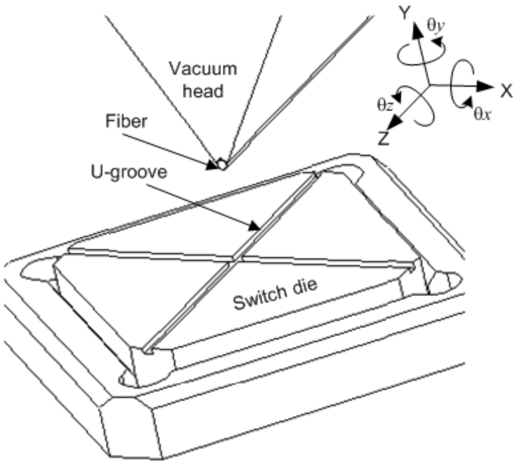
Desired assembly configuration

Assembly Process Analysis

- **Assembly Uncertainties**

Four kinds of assembly errors

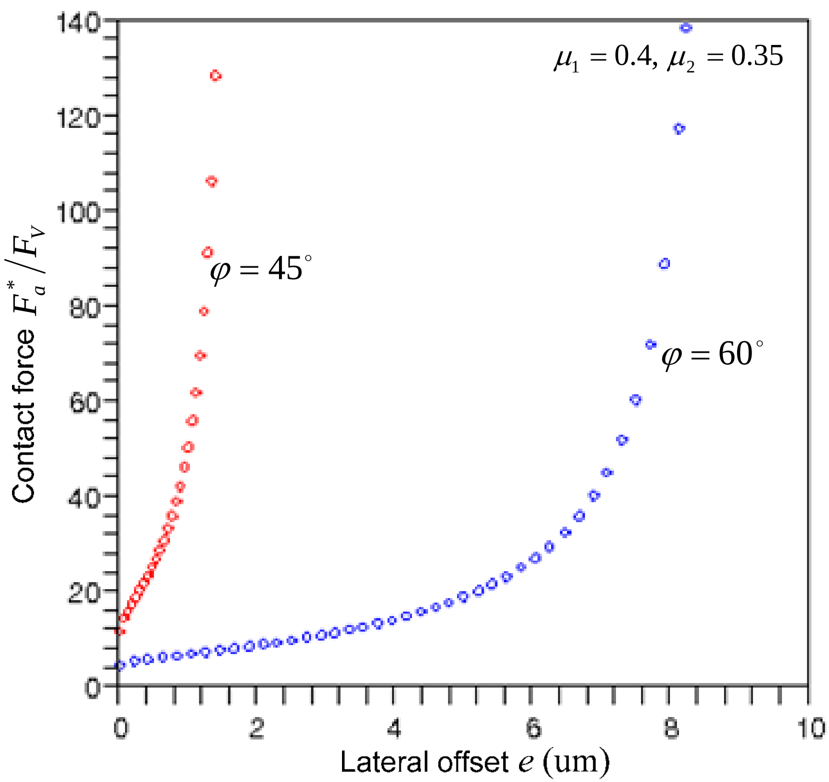
- ✓ **Lateral offset**
- ✓ **Yaw angle offset**
- ✓ **Tilt angle offset (studied in future work)**
- ✓ **Axis offset (don't affect mating, but affect light coupling)**



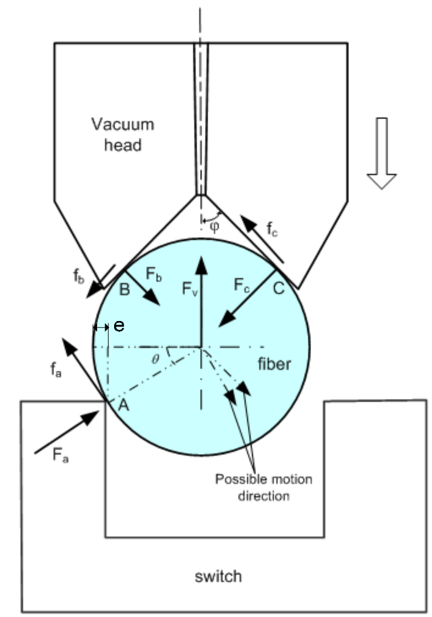
Fiber insertion operation

Assembly process analysis

Without fiber slip or rotation during insertion



Threshold curve of contact force for secure grip of fiber



Quasi-kinematics model of contact

Fa: contact force

Fv: vacuum force

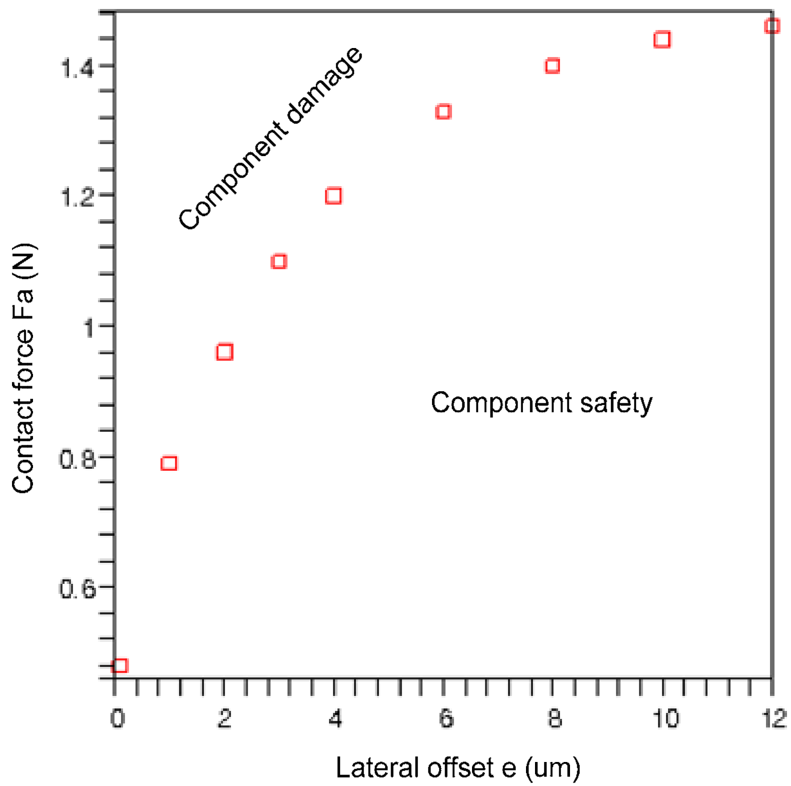
μ1 and *μ2*: coefficients of friction of point A and C

φ: half angle of vacuum head

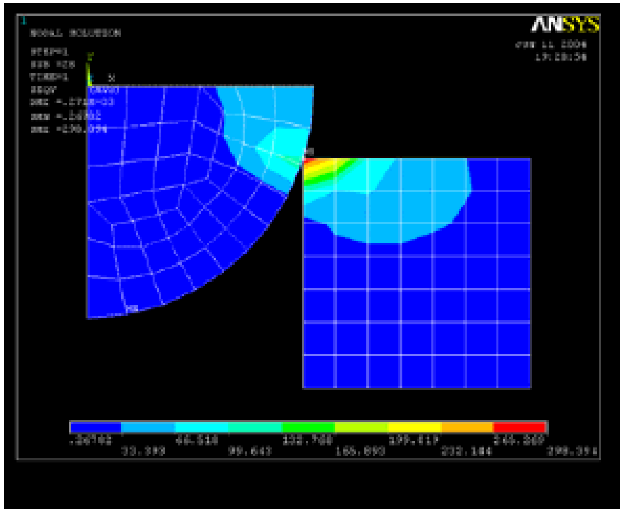
Assembly process analysis

➢ Component protection

- Contact forces have to be less than the threshold



Threshold curve of contact force for component safety

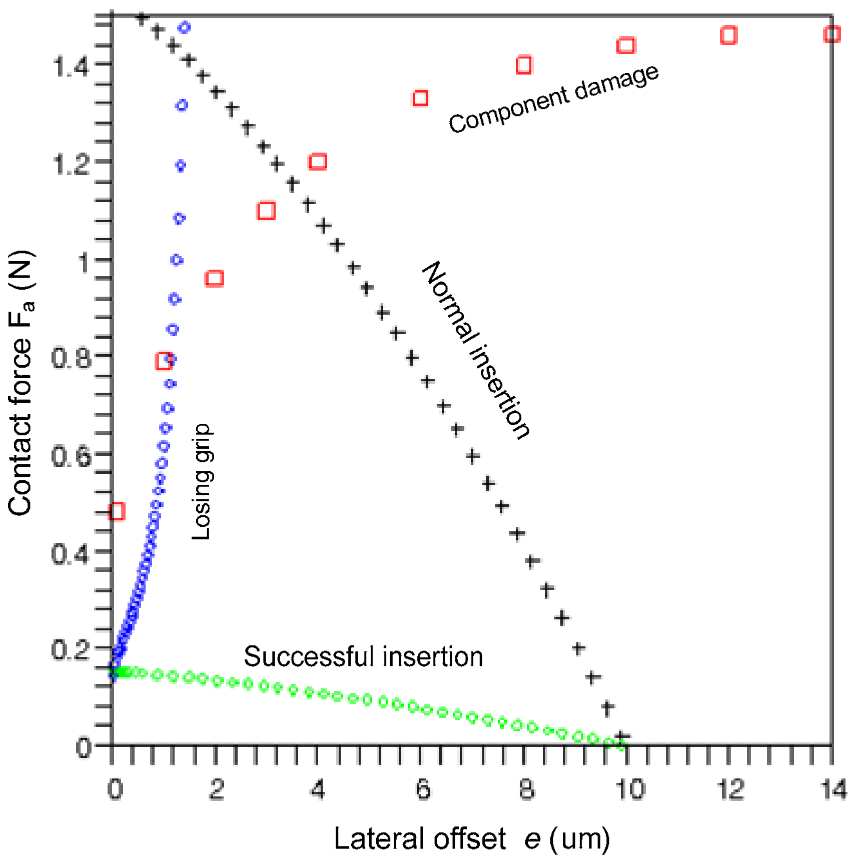


Component damage simulation by ANSYS

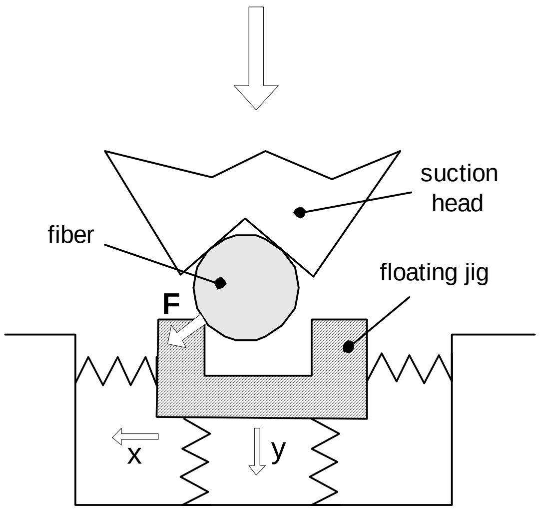
Assembly process analysis

➢ **Successful insertion condition:**

- **Without losing-grip**
- **Without component damage**



Successful insertion analysis



Environment compliance have a significant effect on performance in terms of contact force and grip

Assembly process analysis

Requirements of Assembly

- **Max allowable angular error α_{max} = 0.05 deg, and lateral error e_{max} = 10 um,**

(the accuracy that normal precision PnP can reach)

- **Isotropic translational compliance in all direction**

$k_{LX} = k_{LY}$ = 26 mN/um

- **Required angular compliance**

k_T = 11Nmm/deg

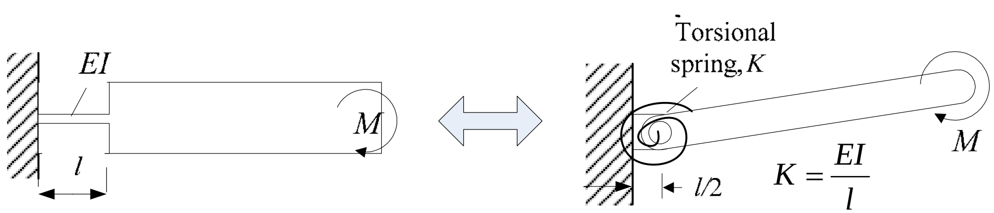
Flexure-based Fixture Design

➢ Flexure-Based Mechanisms

Flexures are compliant joints that provide motion by material deformation within elastic range

- **No backlash and clearance**
- **Not need assembly**
- **Compact size**
- **Can be designed based on stiffness**

Joints' K_q, K_p $\xrightarrow{\text{Flexure design}}$ **Flexure type and size**

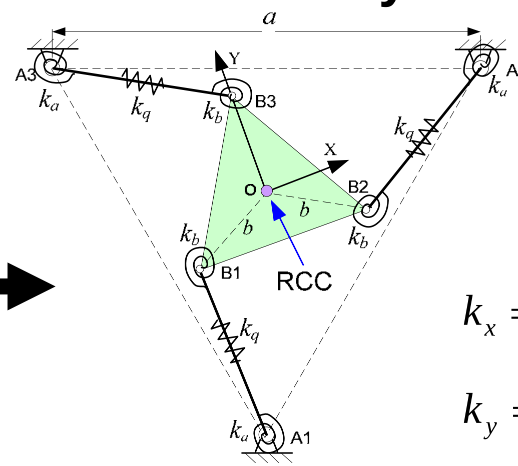


An example conversing normal joint to flexure

Flexure-based Fixture Design

- **A flexure-based fixture for MEMS assembly**

x, y, θ Compliance
$K_x = K_y$ = 26 mN/um
K_θ =11Nmm/deg



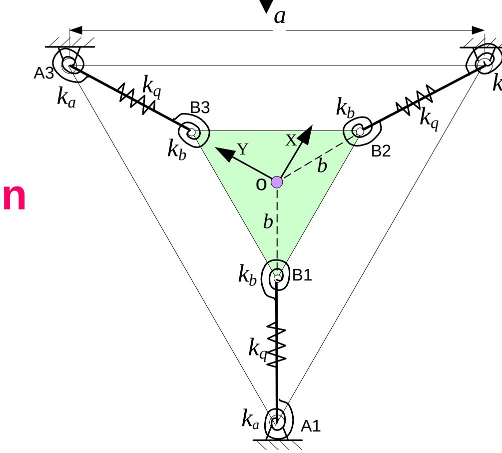
Topological synthesis

$$k_x = \frac{3}{2}(k_q + \frac{1}{q}k_\varphi + \frac{1}{q}k_\psi)$$

$$k_y = k_x$$

$$k_\theta = 3k_q b^2\cos^2(\varphi+\theta) + \frac{3k_\varphi}{q^2}b^2\sin^2(\varphi+\theta) + \frac{3k_\psi}{q^2}(b\sin(\varphi+\theta)+q)^2$$

Configuration optimization



$$k_x = \frac{3}{2}(k_q + \frac{1}{q}k_\varphi + \frac{1}{q}k_\psi)$$

$$k_y = k_x$$

$$k_\theta = \frac{3k_\varphi}{q^2}b^2 + \frac{3k_\psi}{q^2}(b+q)^2$$

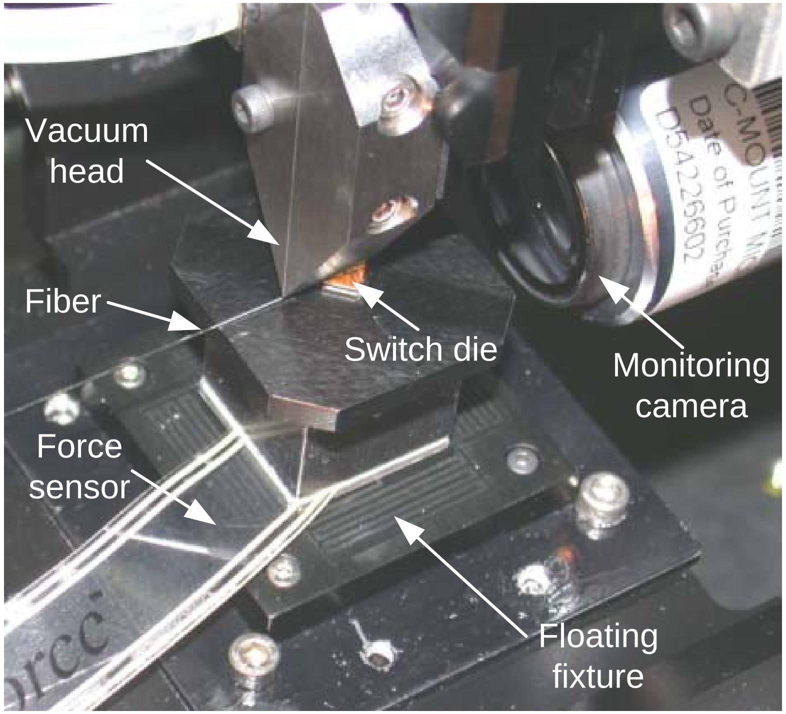
k_q, k_φ, k_ψ

Flexure design

Flexure-based device

Experiment Results

➢ Experiment Setup



A flexure-based passive micro assembly system

Vacuum head: V-shaped head, providing 25.6 mN suction force to the fiber

Floating fixture: flexure-based mechanism, providing required compliance in x-y-θ axes

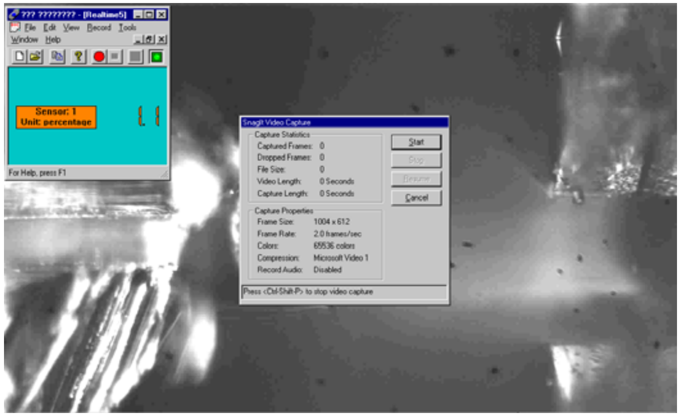
Force sensor: monitor the insertion force

Monitoring camera: monitor the insertion errors

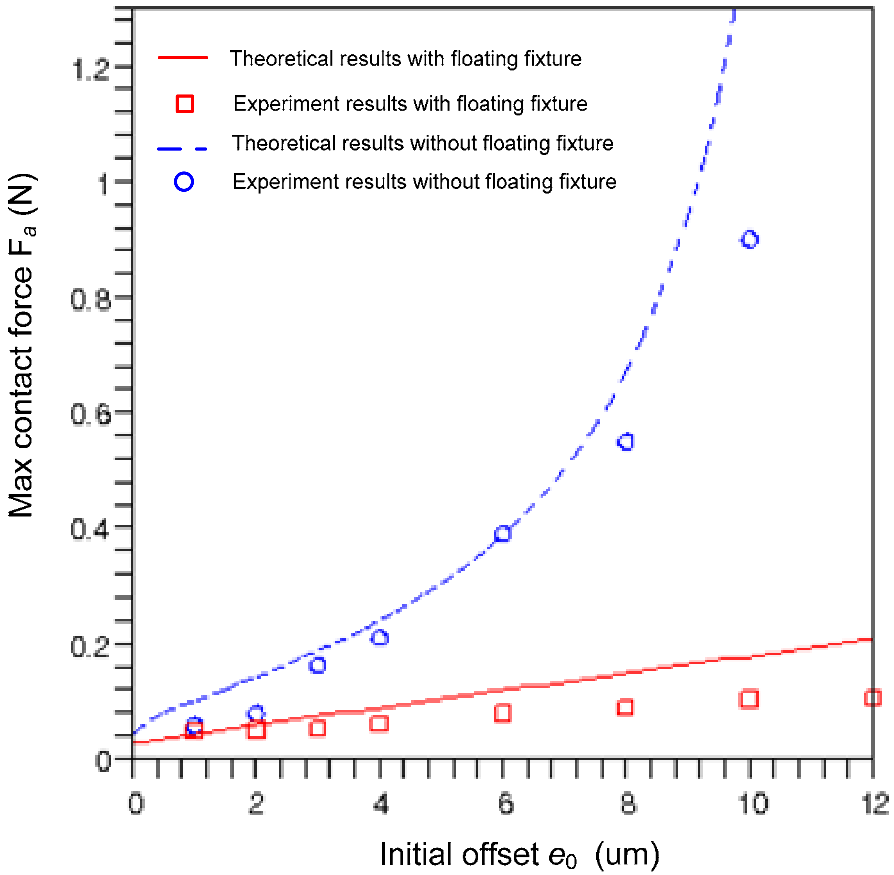
6-axes stage: set the required initial errors for test

➢ Results and Analysis

Fiber insert into U-groove without help of the floating fixture



Fiber insert into U-groove successfully with help of the floating fixture



Comparison of the maximum contact forces

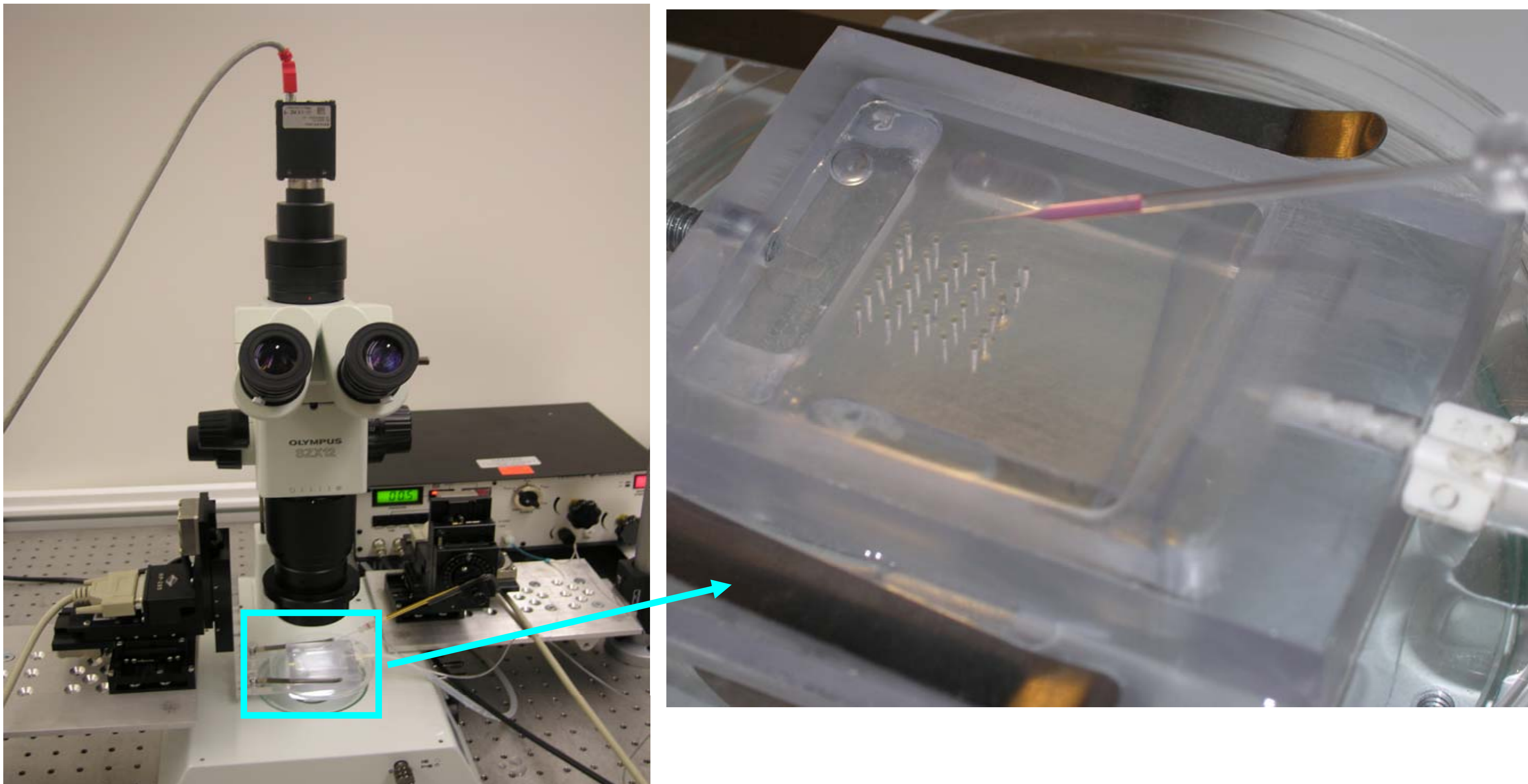
Back

Microrobotic Cell Injection

- Cell Patterning
- Determine 3D information from 2D imaging
- Cell Injection

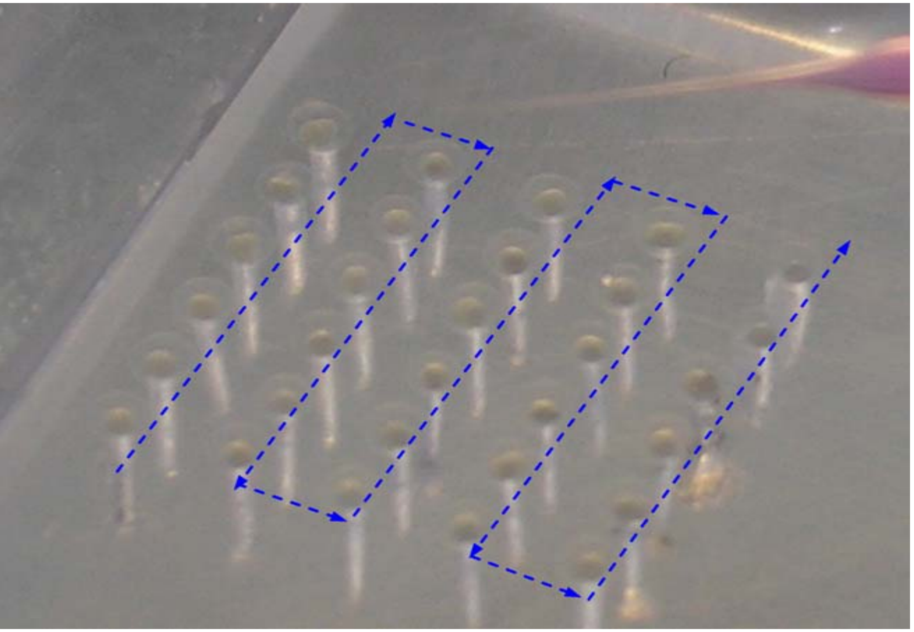
Wang, WH, Hewett, D, Hann, CE, Chase, JG and Chen, XQ (2008). “Machine vision and Image Processing for Automated Cell Injection,” Proc 2008 IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA08), ISBN: 978-1-4244-2368-2, Beijing, China, October 12-15, pp. 309-314.

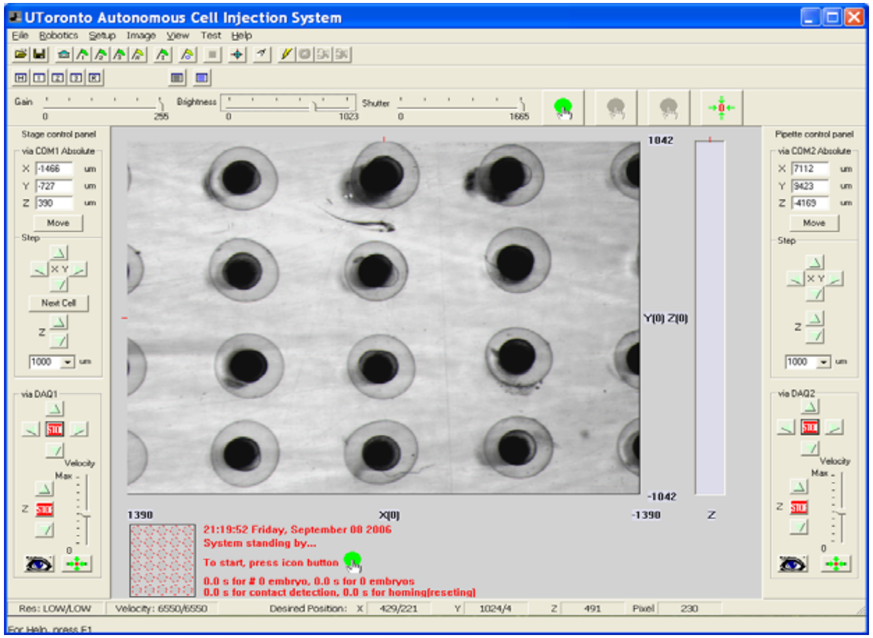
Microrobotic Cell Injection System



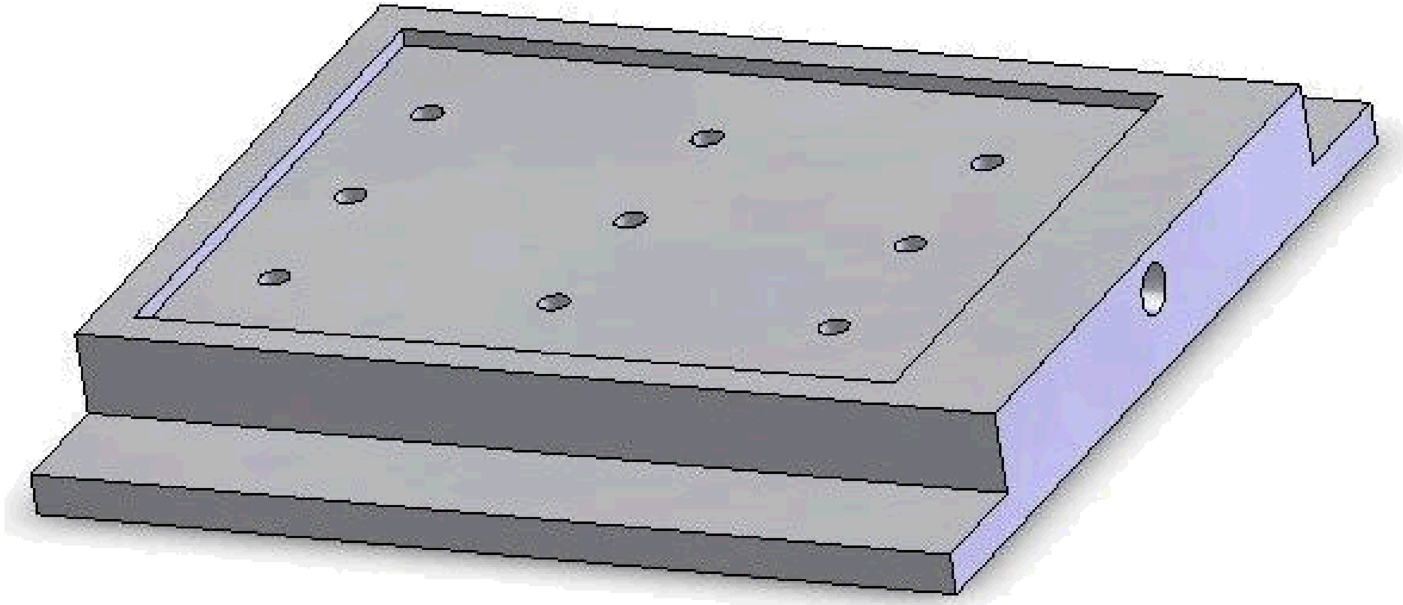
Challenges to Tackle

- Immobilize a large number of cells into a regular pattern
- 3D manipulation with 2D microscopy visual feedback
- Robust image processing
- Coordinately control two microrobots
- Optimization of operation parameters to minimize lysis

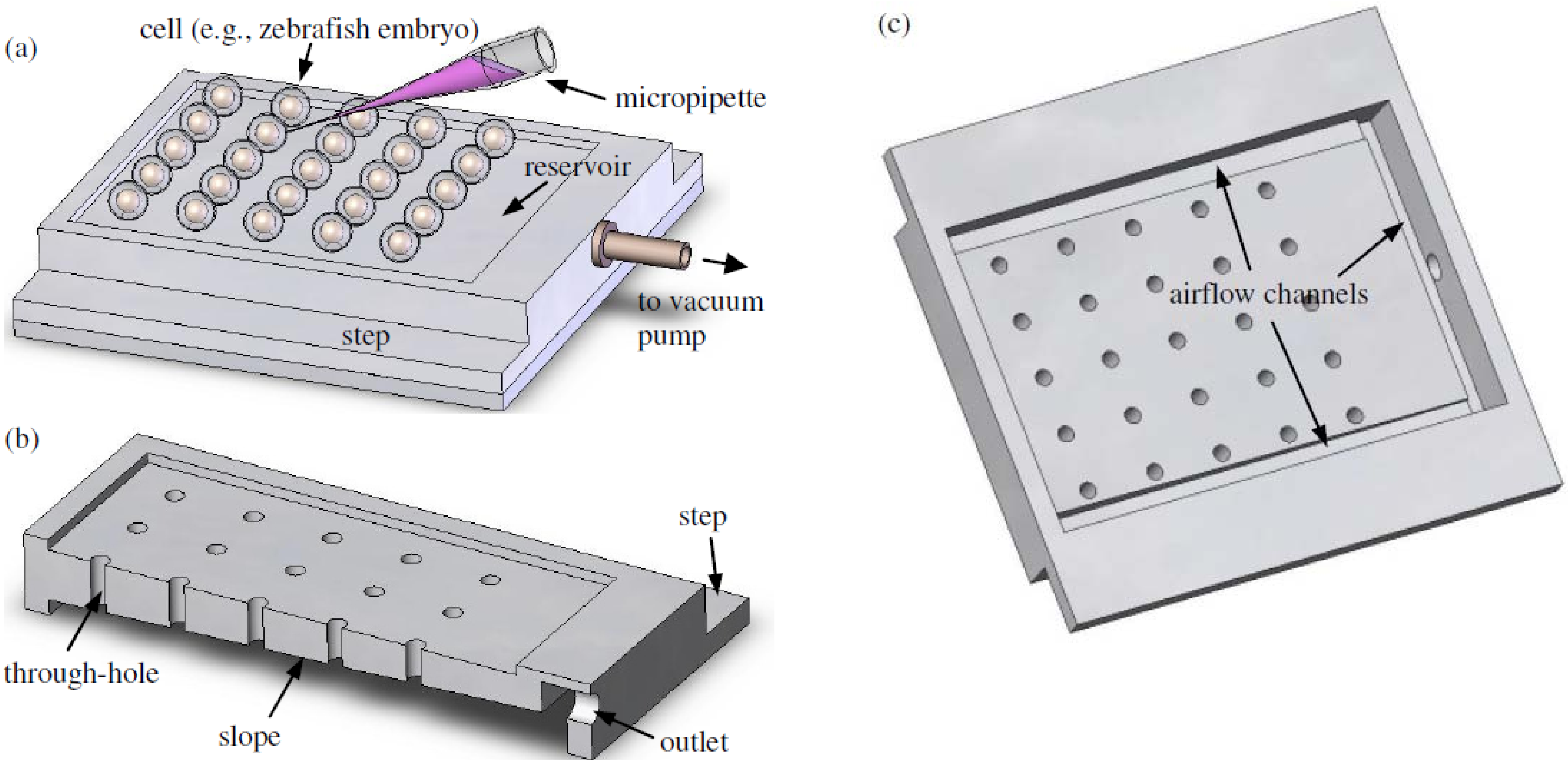




Embryo Holding Device



Detailed structure



Sample Preparation

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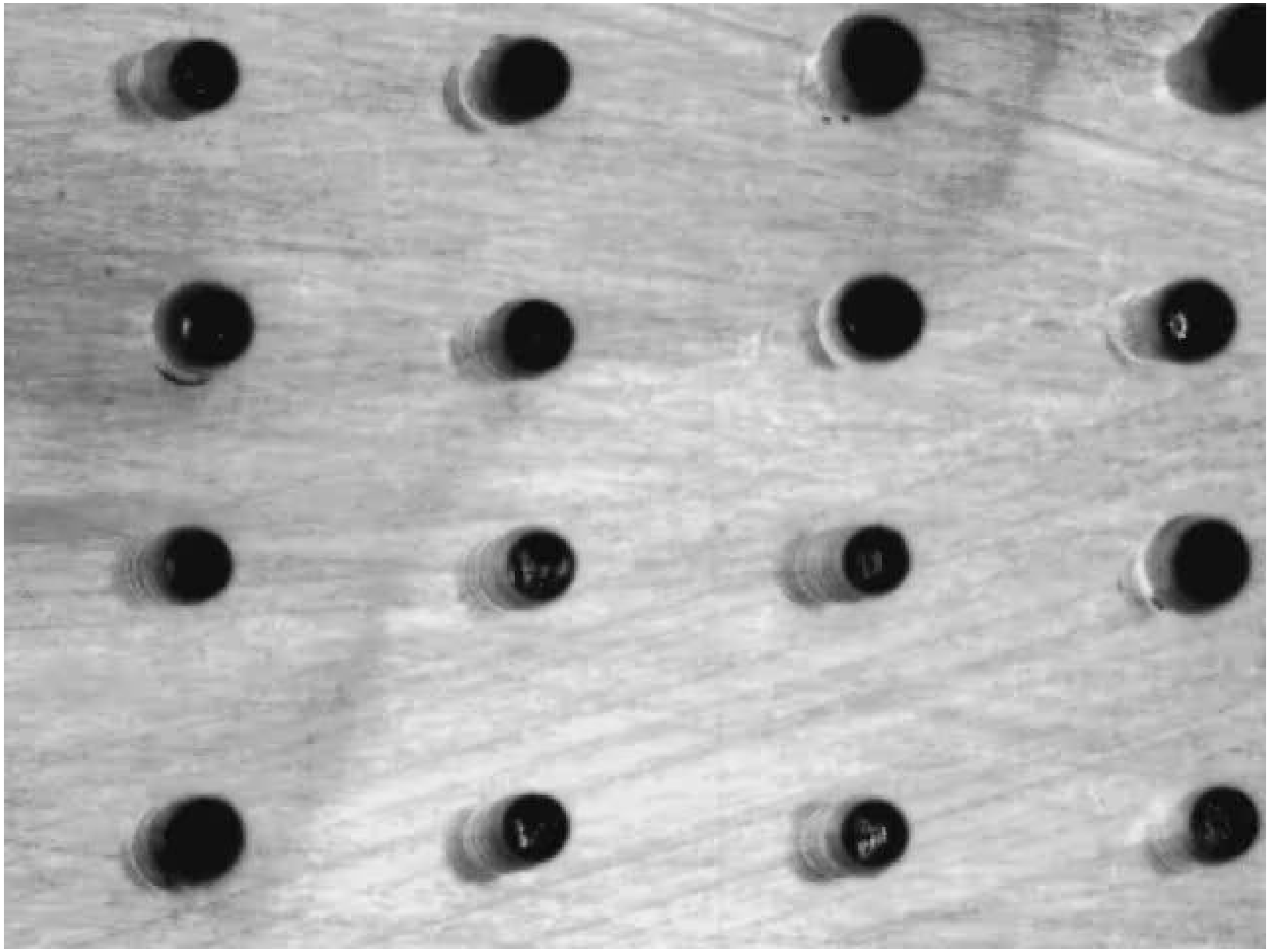
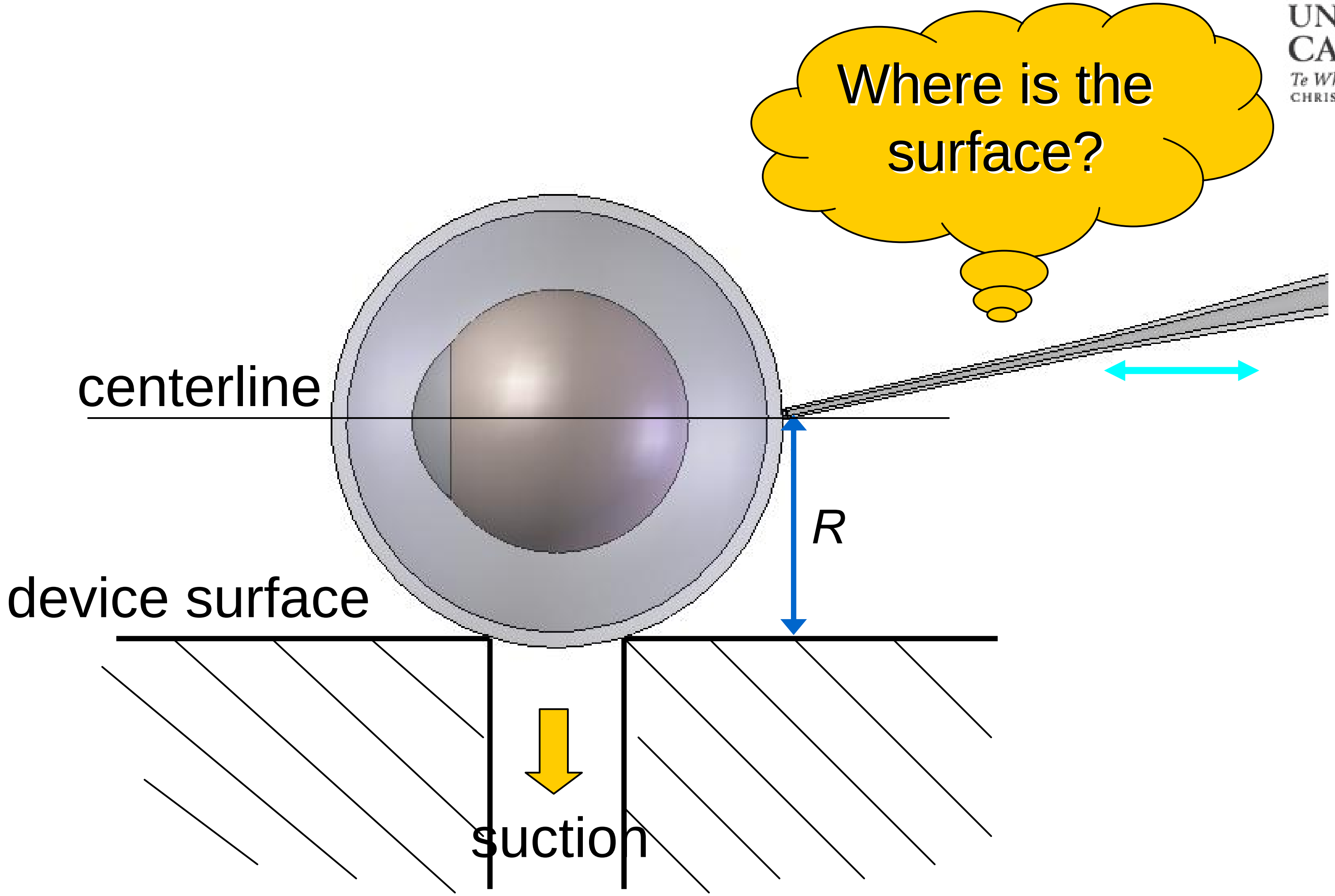
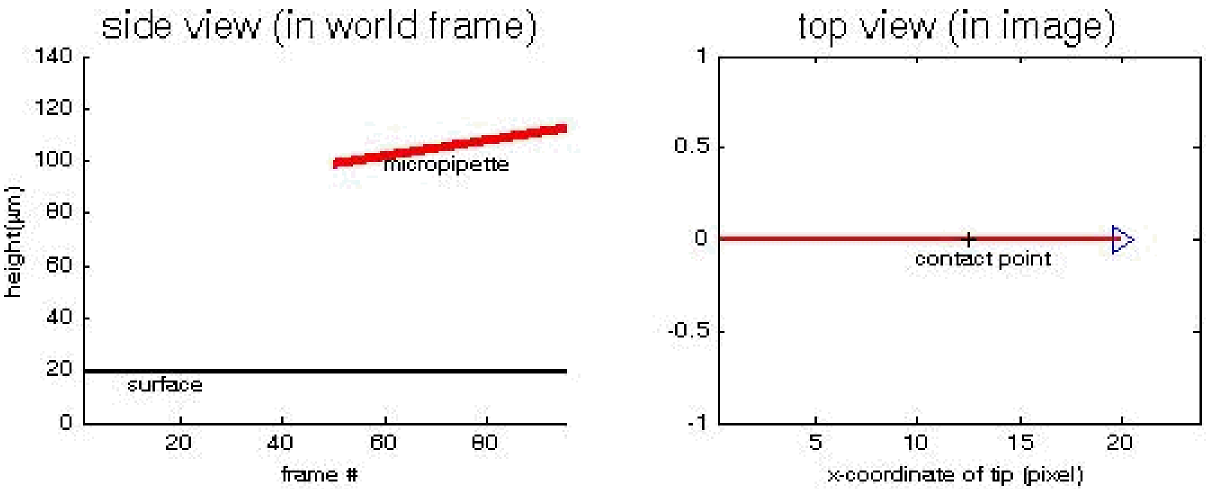


Contact Detection

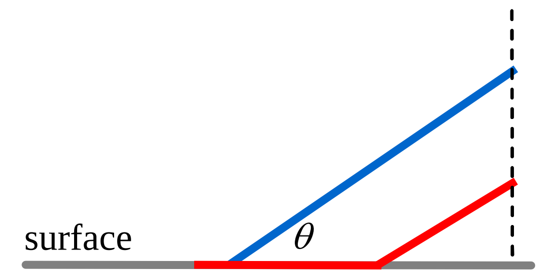


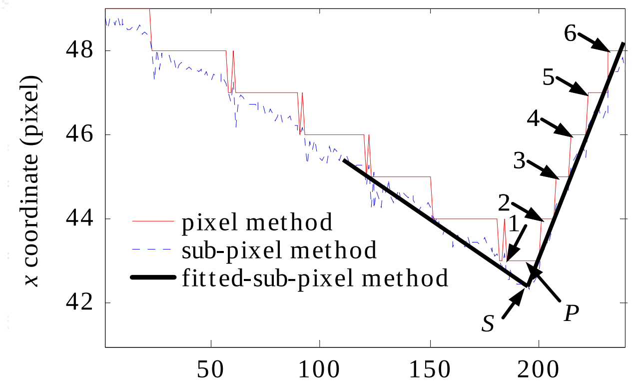
Can we get 3D (Z) information from 2D (image plane x-y) information?

Contact Detection Principle



contact detection procedure animation



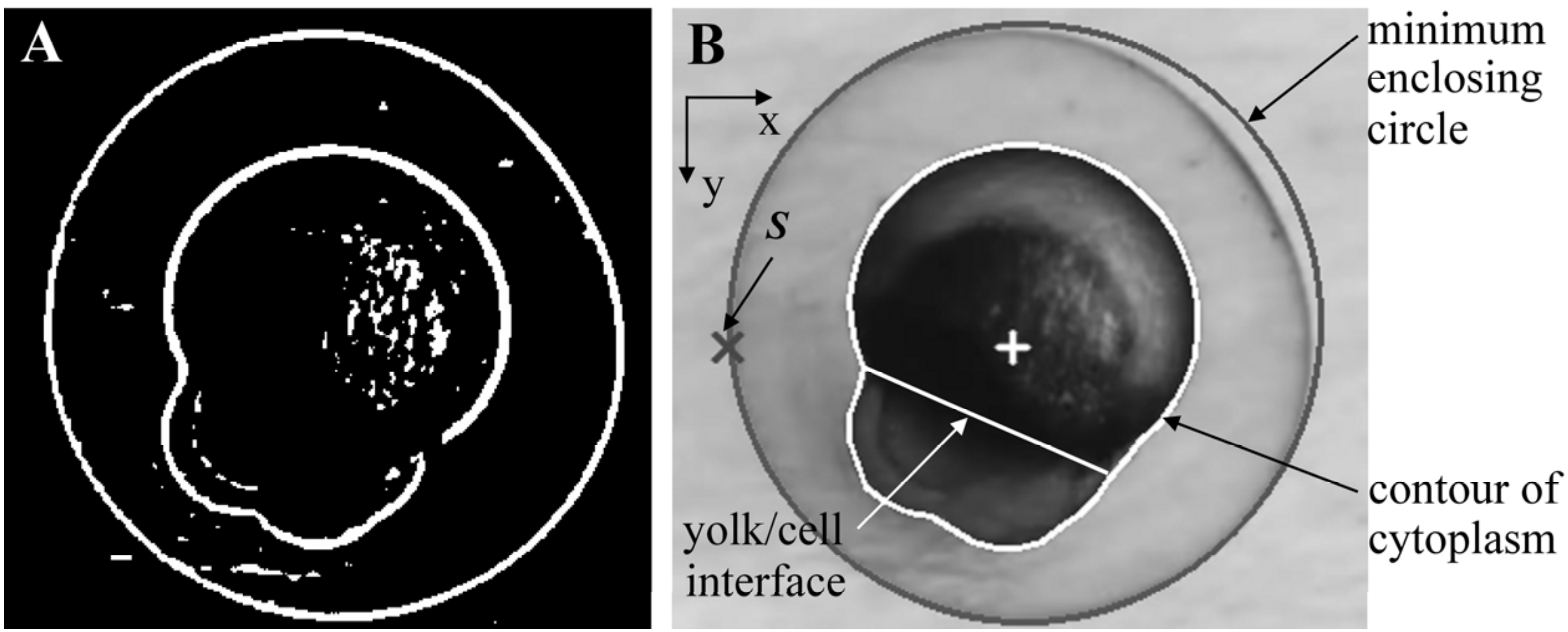


real case

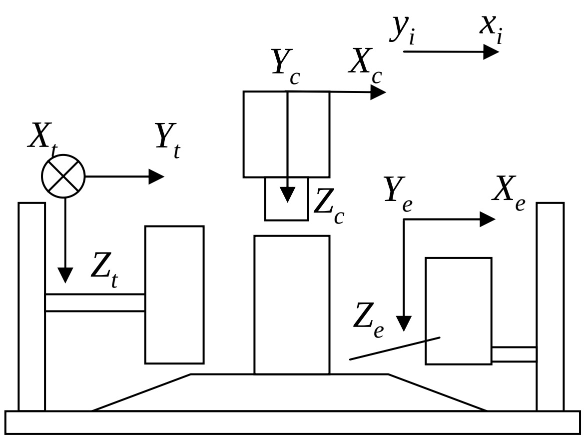
Int. J. Robot. Res., 26, 2007

Recognition of Embryo Structures

- Adaptive thresholding and morphological operations
- Snake tracking and convex deficiency calculations
- Recognition of chorion, cell, yolk, and cytoplasm center

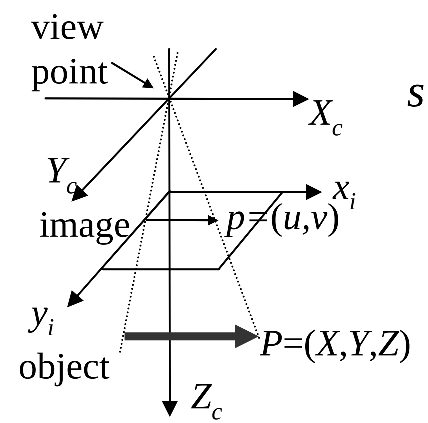


Coordinate Frames & Transformation



$$ {}^{e}R_{c} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} $$

$$ {}^{t}R_{c} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} $$



$$ s = \begin{bmatrix} s_x & 0 \\ 0 & s_y \end{bmatrix} $$

$$ s\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} X \\ Y \end{bmatrix} $$

$$ s\,{}^{i}p = {}^{c}P \quad (1) $$

microrobotic frames vs. camera frame

$$ {}^{e}P = {}^{e}R_{c}\,{}^{c}P + {}^{e}t_{c} $$

$$ {}^{t}P = {}^{t}R_{c}\,{}^{c}P + {}^{t}t_{c} $$

(1)

microrobotic frames vs. image frame

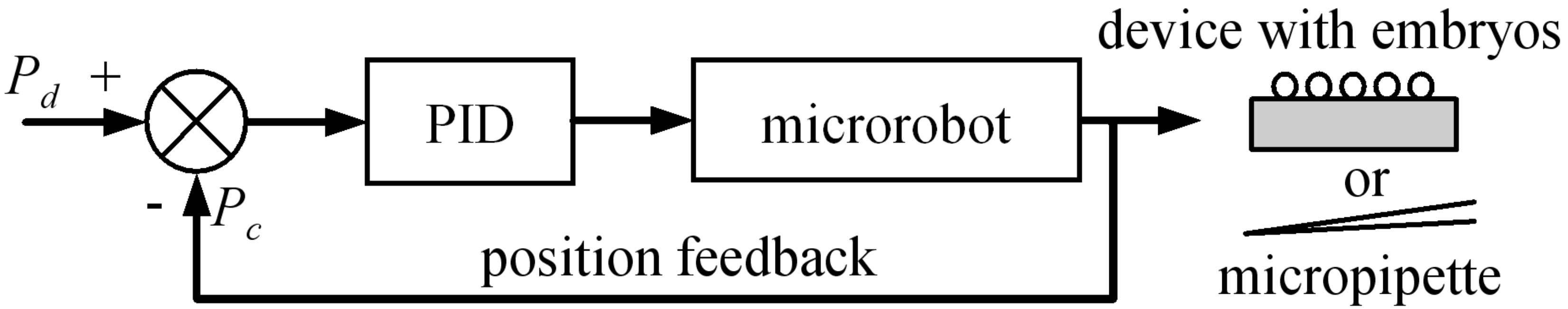
$$ {}^{e}P = {}^{e}R_{c}\,s\,{}^{i}p + {}^{e}t_{c} $$ tip home position

?

$$ {}^{t}P = {}^{t}R_{c}\,s\,{}^{i}p + {}^{t}t_{c} $$ initial cytoplasm centroid

Looking-then-Moving

- Looking in image for initial positions of:
  - ➢ the tip
  - ➢ the deposition point
- Where to move in microrobotic frames?
  - ➢ coordinate frame transformation
- How to move?
  - ➢ position feedback from microrobots only



Injection Control Sequence

contact detection → batch injection

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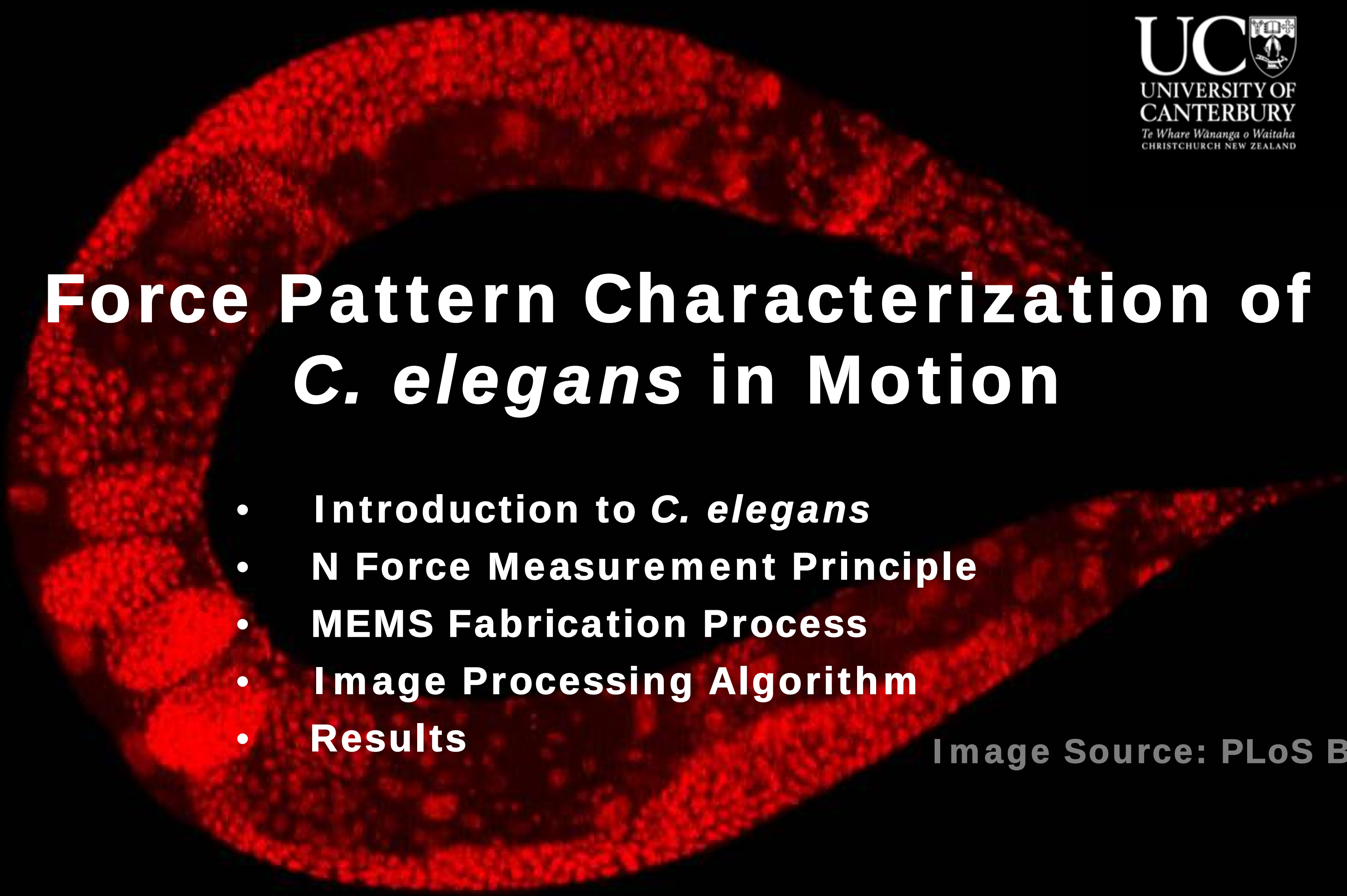


Force Pattern Characterization of *C. elegans* in Motion

- Introduction to *C. elegans*
- N Force Measurement Principle
- MEMS Fabrication Process
- Image Processing Algorithm
- Results

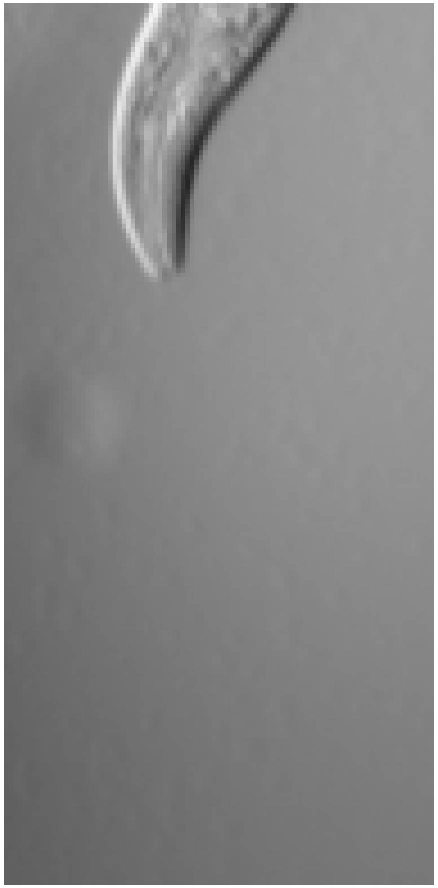
Image Source: PLoS Biol

Ali Ghanbari, Volker Nock, Wenhui Wang, Richard Blaikie, J. Geoffrey Chase, XiaoQi Chen, and Christopher E. Hann (2008). "Force Pattern Characterization of C. elegans in Motion", 15th Intl Conf on Mechatronics and Machine Vision in Practice (M2VIP), Auckland, New Zealand, Dec 2-4,CD-ROM.

C. elegans – Locomotion

C(aenorhabditis) elegans

- free-living nematode (roundworm)
- about 1 mm in length, 100μm in width
- lives in temperate soil environments
- used extensively as a model organism



C. elegans was the first multicellular organism to have its genome completely sequenced (1998)

Challenging because:

- *C. Elegans* are very small**:**
  - **cannot use conventional force measurement techniques**
- *C. Elegans* are living organisms**:**
  - **non-intrusive measurement technique required**

Cellular Force Modelling

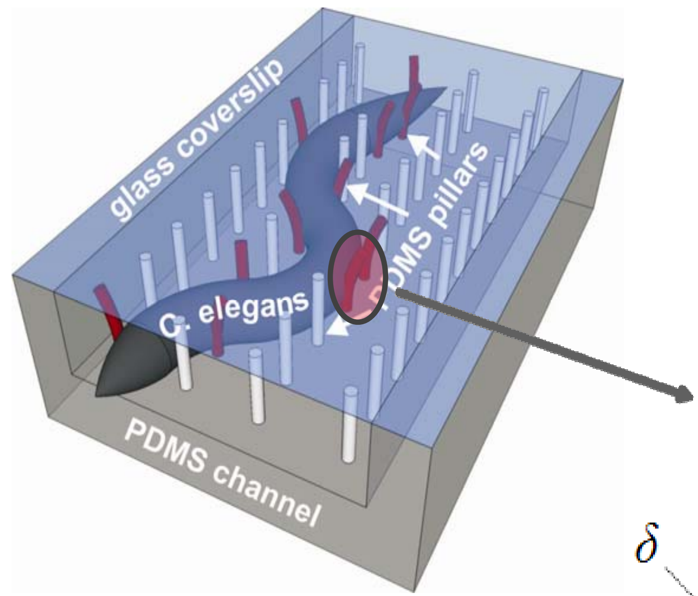
- At force point:
  Bending + Shear

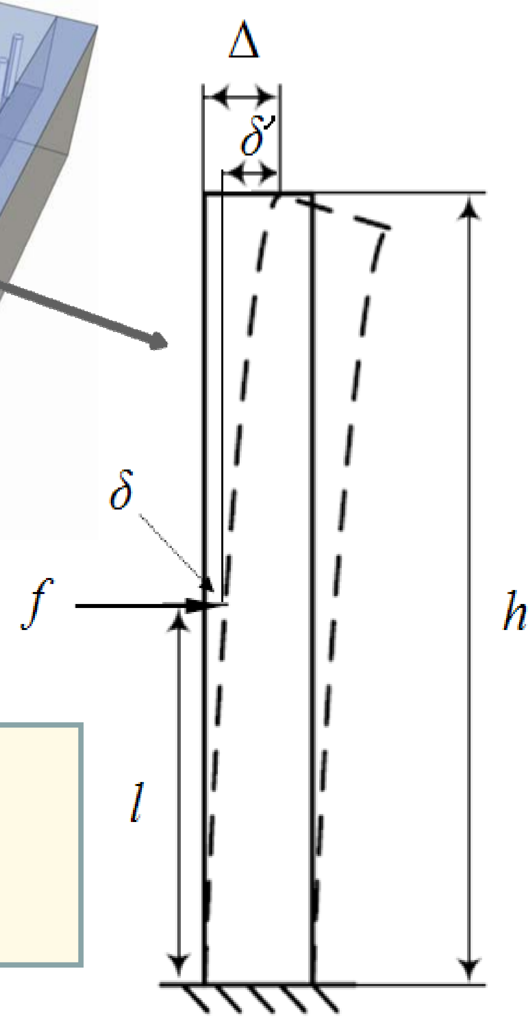
$$\delta = \left(\frac{l^3}{3EI} + \frac{20(1+\gamma)l}{9AE}\right).f$$

- From force point to the free end of the pillar:
  Just Bending

$$\delta' = \frac{l^2}{2EI}(h-l).f$$

I: moment of inertia
E: Young's modulus
Y: Poisson's ratio

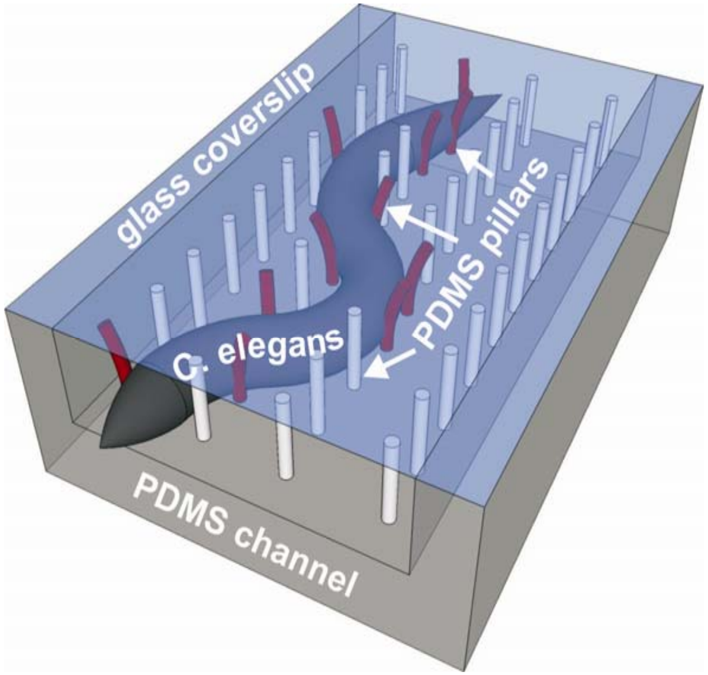




$$\Delta = \delta + \delta'$$

$$\boxed{f = \frac{\Delta}{\left(\frac{l^3}{3EI} + \frac{20(1+\gamma)l}{9AE}\right) + \frac{l^2}{2EI}(h-l)}}$$

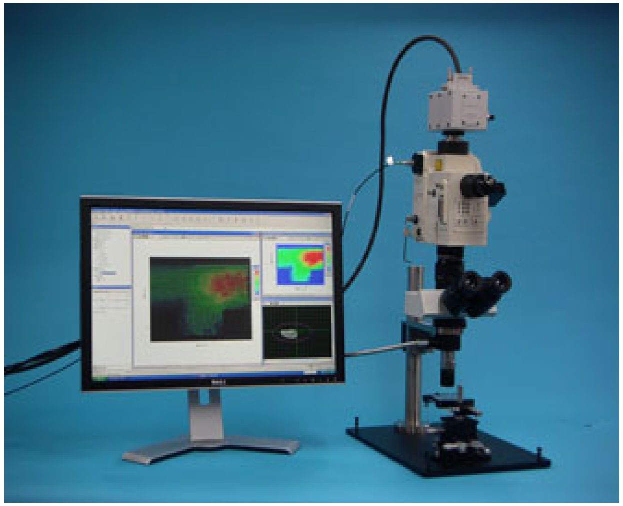
Detecting Pillar Deflection



Parameters for Pillar Array:

- stiffness of silicone
- pillar diameter
- spacing
- height

Image capture and processing setup



MEMS Fabrication

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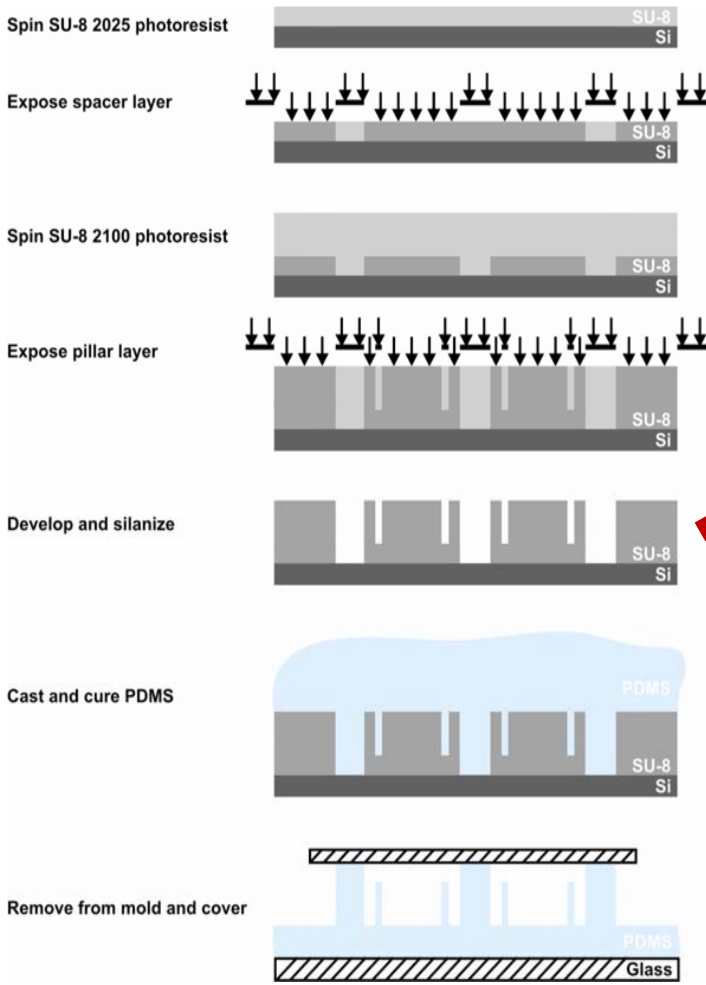

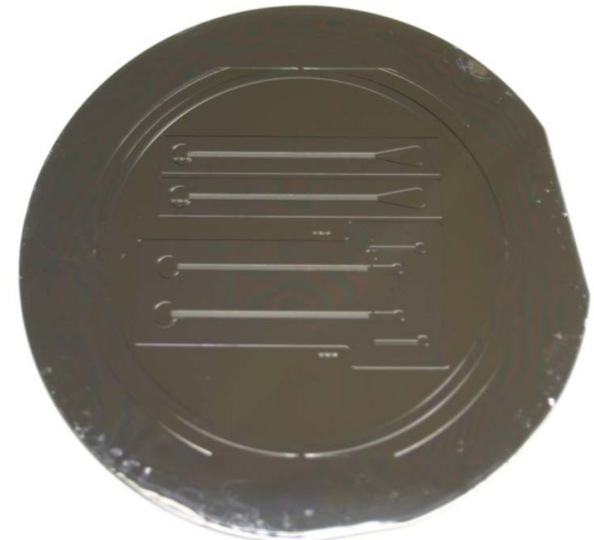

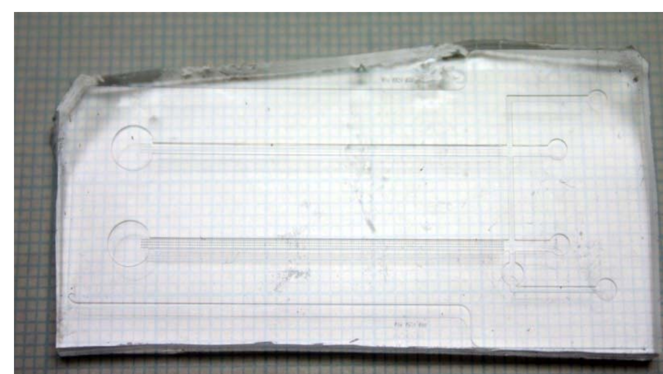

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Device Molds

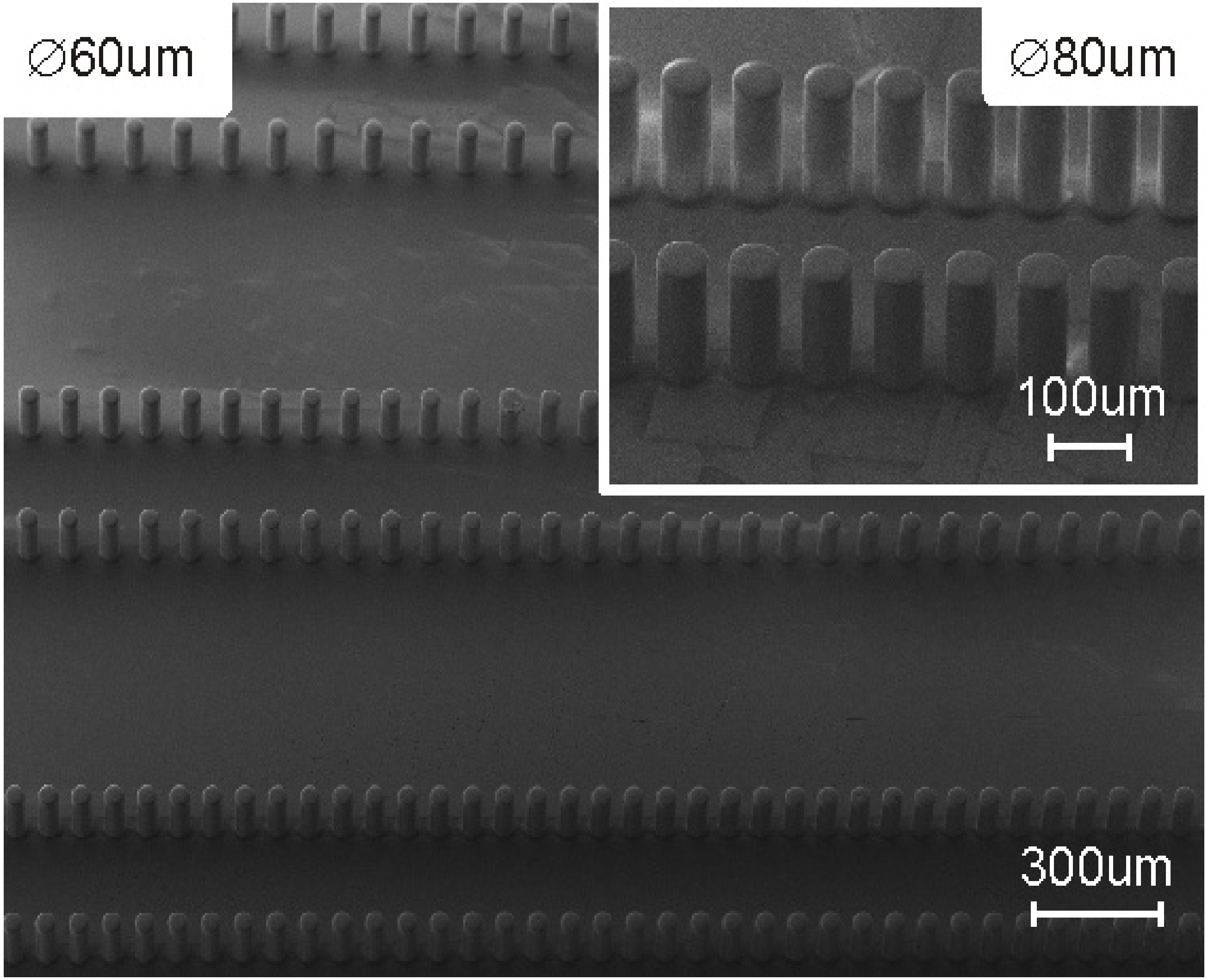


Image processing

- Without loss of generality, three specific pillars targeted for image processing
- Frames converted to black and white to have binary images
- Three zones defined to extract each pillar image in an assigned square window
- A Boundary Tracing Algorithm developed and adapted to trace the outline of the outer circle of the deflected pillars

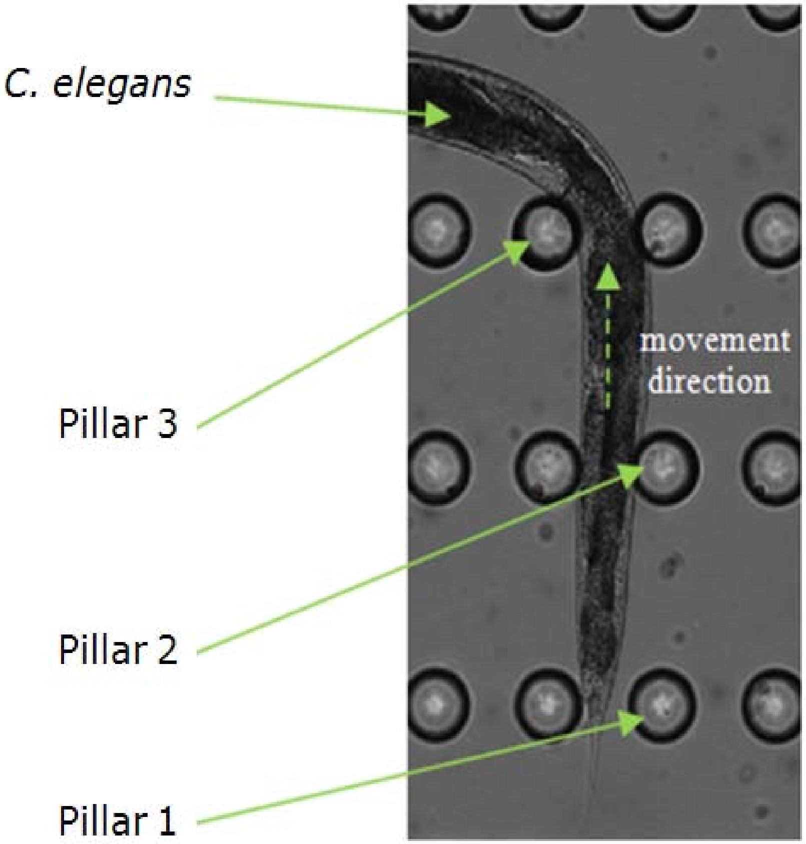


Image processing Algorithm

- Scanning the square window from bottom left: P0
- Searching the 3×3 neighborhood of the current pixel in an anti-clockwise direction.
- The circle point tracing is repeated up to detecting nth pixel Pn .

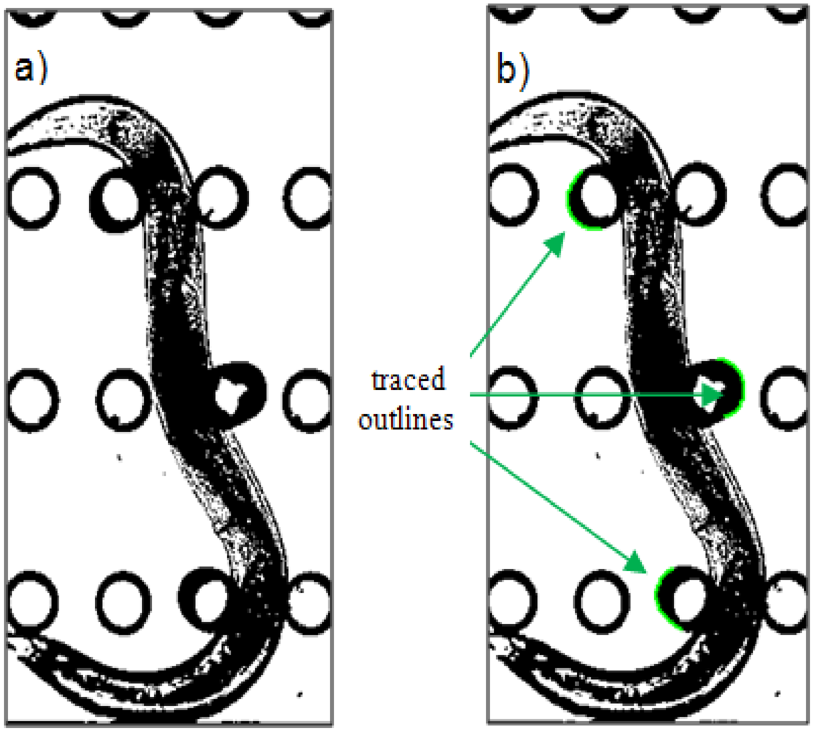
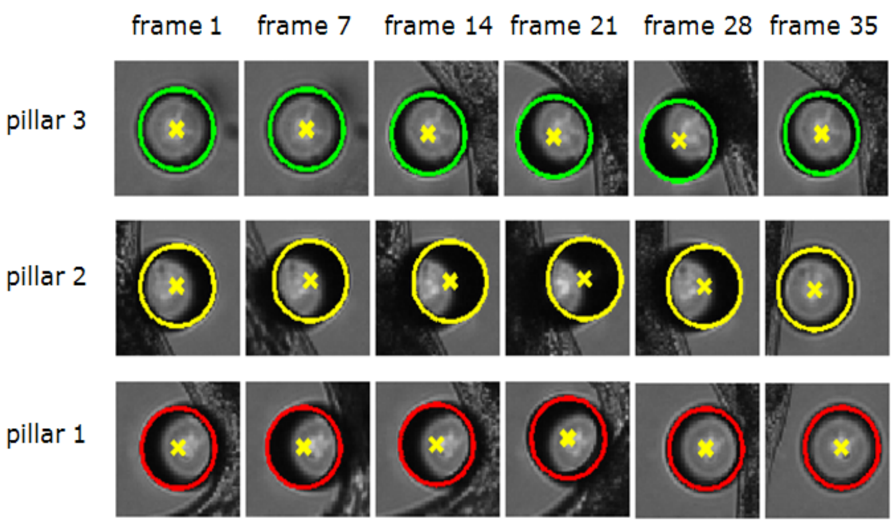
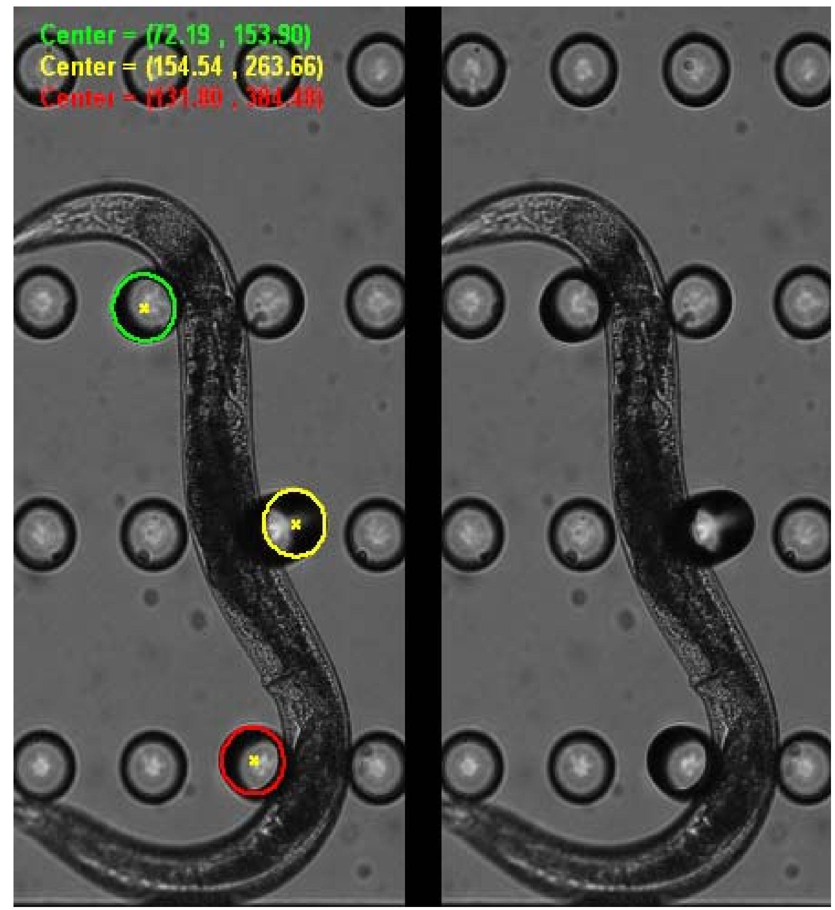


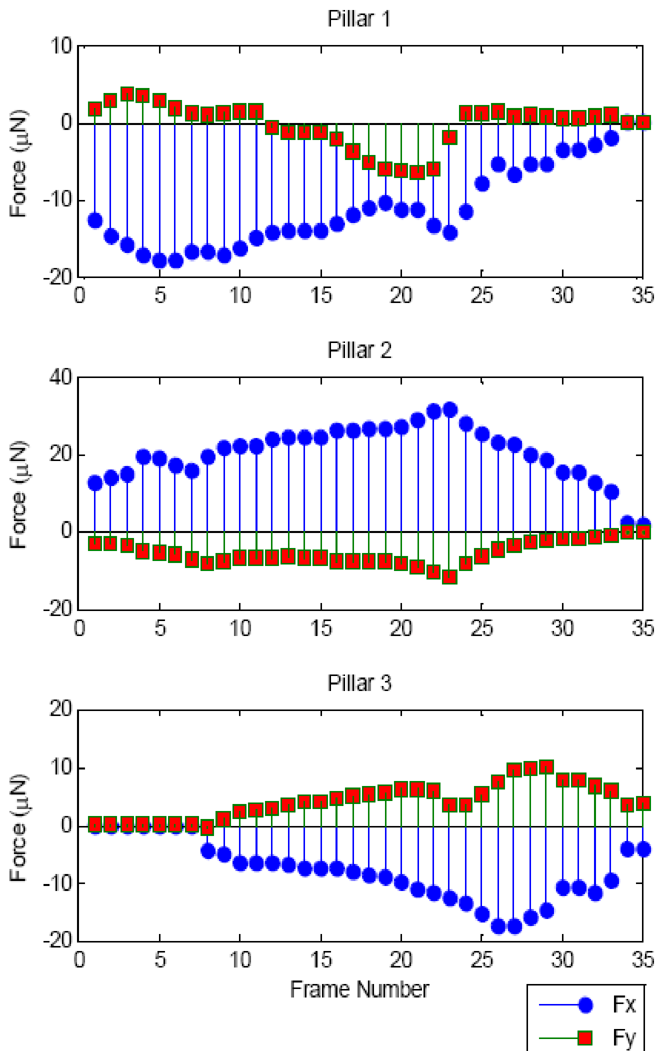
Image processing Algorithm

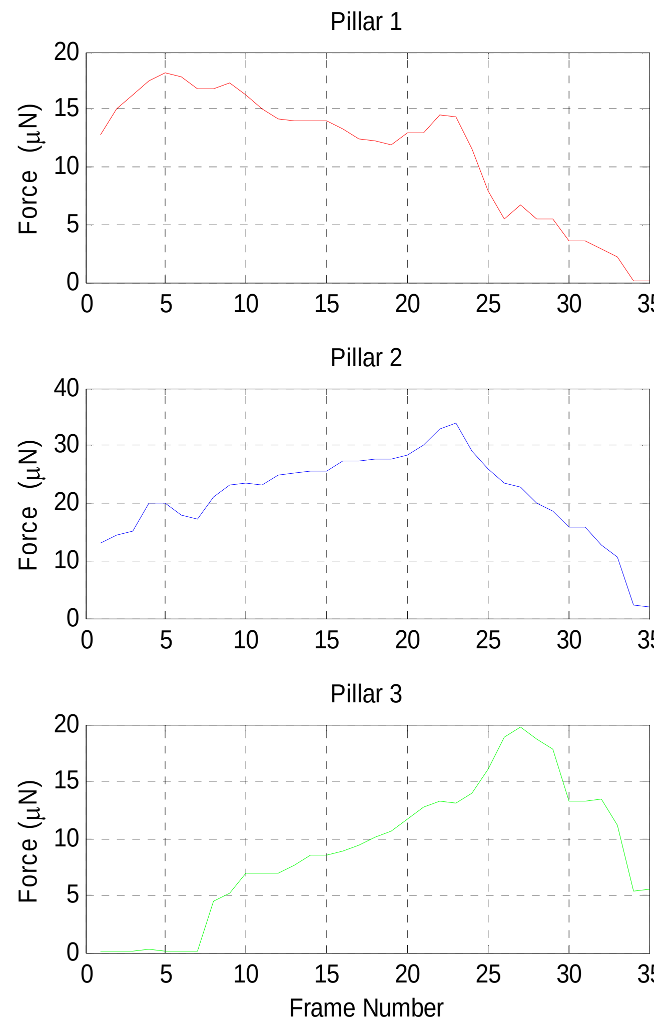
- A least-square fitting algorithm was employed to fit a circle to the traced points





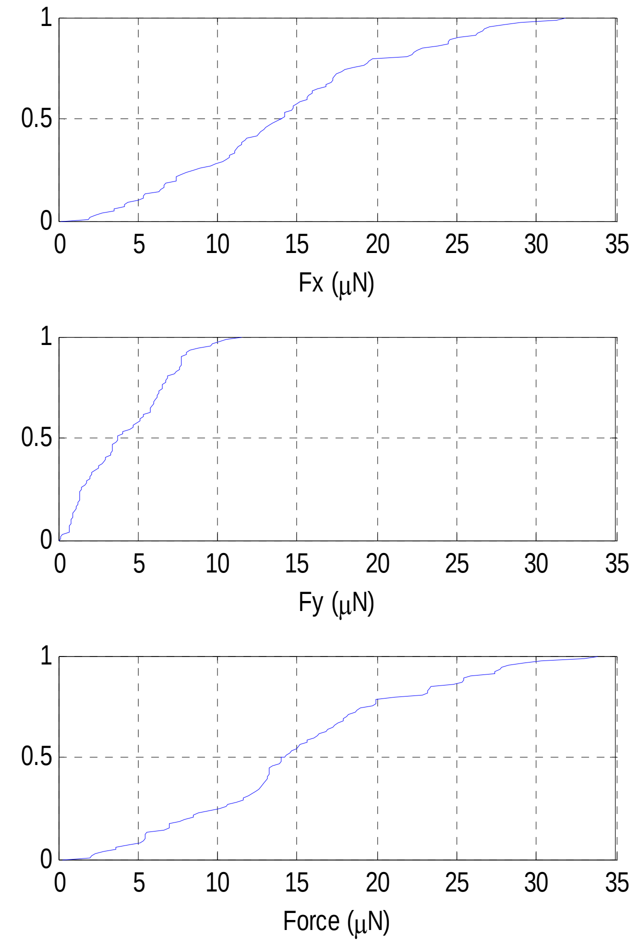
MAX FORCE	PILLAR 1	PILLAR 2	PILLAR 3
$\lvert f_x \rvert$ (μN)	17.93	31.85	17.48
$\lvert f_y \rvert$ (μN)	6.58	11.52	10.08
$\lvert f \rvert$ (μN)	18.15	33.87	19.76





Cumulative Distribution of Calculated Forces

- Sorting the all calculated forces of three pillars except zero ones from smallest to largest and distributing them between 0 to 1 with steps of one over the number of sorted forces.
- A nearly linear cumulative distribution function (CDF) will be obtained, which implies an approximately uniform distribution of forces.
- It shows a highly variable and continuous force level produced by the worm, which is in accordance with biological results and the anatomy of *C. elegans.*



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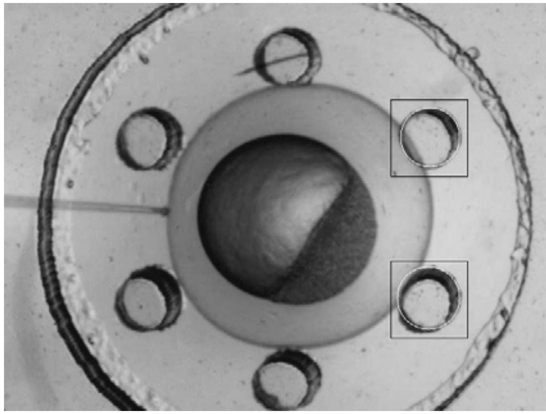
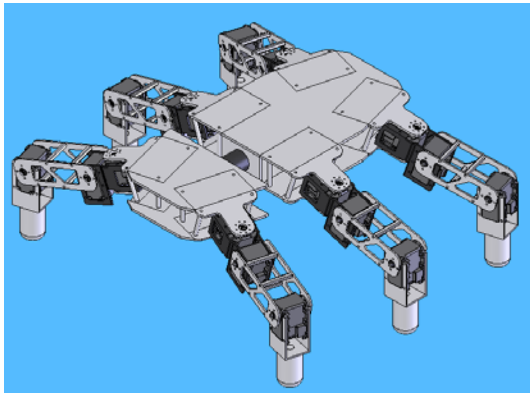
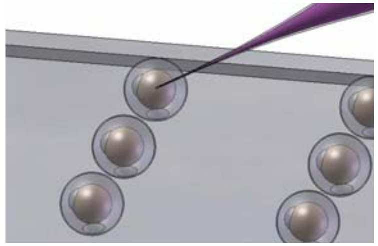
Conclusion & Future Work

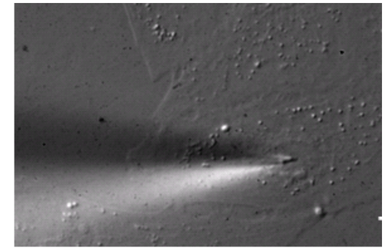
- Assistive robotic devices
  - Prosthetics, Rehabilitation
  - Active assistant
- Biologically inspired robots
  - Biomimetics study
  - Novel micro actuator and mobility control
  - Situational awareness (feeler, vision, tactile, sound)
- Human machine interface technology
  - Augmented reality
  - Haptics device for virtual presence and virtual training
  - Brain-computer interface
- Mobile robotics
  - Mobility: hybrid wall climbing mechanism (Bernoulli pad++), untethered
  - Sensing: vision for motion sensing in place of expensive IMU
  - Environmental / resource measurement, monitoring
  - Automating complex tasks in natural environment.
- Energy harvesting
  - Convert mechanical energy to electric power. Cost & efficiency.
  - Self-powered wireless instrument

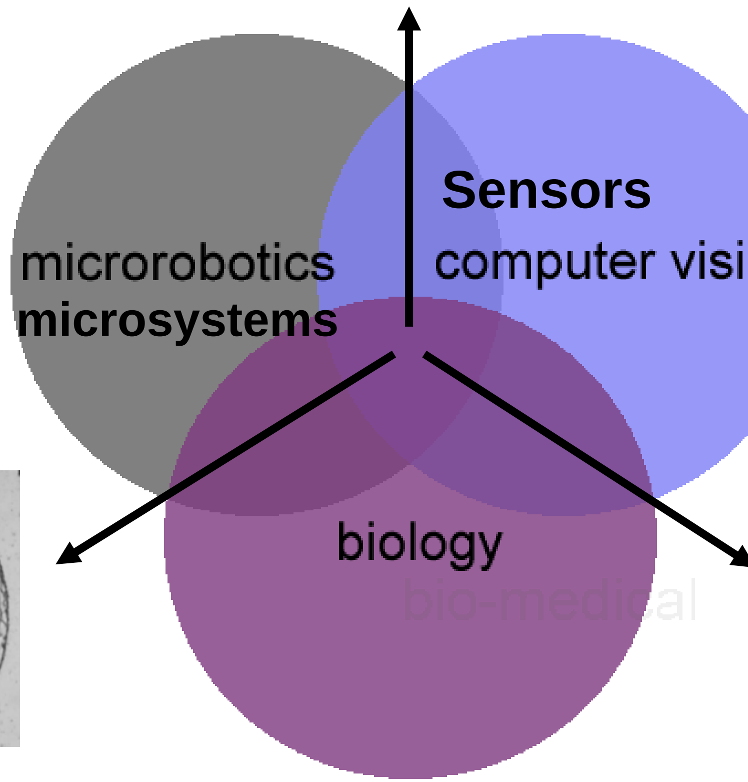


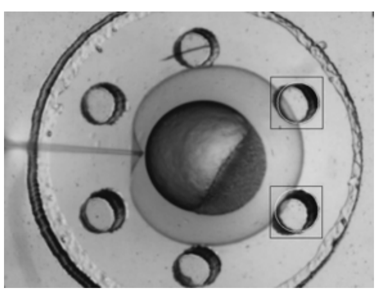


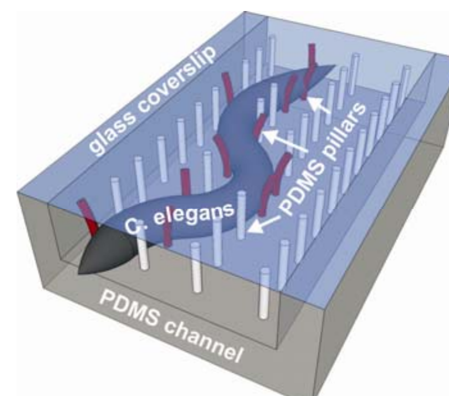
Biomechatronics











Questions ?